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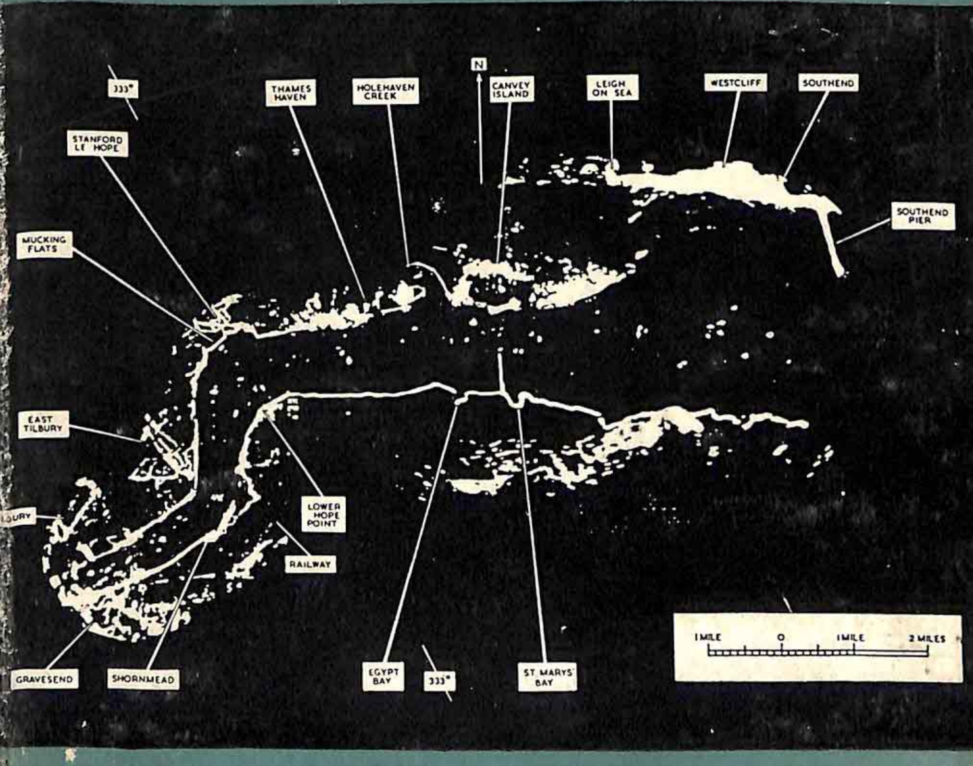
RADAR

simply explained

by R. W. HALLOWS

Second edition revised and enlarged



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RADAR

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By the same author

TELEVISION SIMPLY EXPLAINED

WIRELESS SIMPLY EXPLAINED

ATOMS AND ATOMIC ENERGY

RADAR

simply explained

by

R. W. HALLOWS

T.D., M.A.Cantab., M.I.E.E.,

Member, Société des Ingénieurs Civils de France
Late Chief Instructor in Radar, 6th Anti-Aircraft Group School

With a Foreword by

GENERAL SIR F. A. PILE, BT.

G.C.B., D.S.O., M.C.,

Commander-in-Chief A.A. Command,
1939-1945

SECOND EDITION
REVISED AND ENLARGED

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To

R. M. H.

who helped so much

Foreword

BEFORE the war hardly anyone had heard the word "radar". A few scientists, thanks to the discoveries of Professor Appleton, had been developing a method of locating aircraft by means of wireless waves; and what a godsend it was that these experiments were so far advanced when war broke out, for without doubt it was our radar installations that made it possible for us to win the Battle of Britain. These installations, primitive as they now appear, did give us sufficient warning of the approach of enemy aircraft to enable the fighters to get up and intercept them, and for the A.A. guns to engage them when they came within range.

When the night "blitz" occurred, once more it was radar that first of all enabled the guns to engage targets which could not be seen or even heard. And later on it gave to our night fighters the power of locating the enemy in the dark.

But the introduction of any scientific device into the Services brings with it a large training problem, and when that scientific device is something so little understood as radar, the problem is greatly intensified. In A.A. Command schools were organised at the beginning of the war, and as each separate training problem arose a new section of each school was set apart to deal with it. The radar section in all schools became the most important of all, because on radar depended everything.

Unfortunately, there was no simple text-book which could be handed out to students and easily understood by them. As knowledge was gained it was put into a form suitable for the ordinary male and female operator, hastily roneo'd off, and sent to all the schools as their text-book.

I think every instructor in radar would have been glad to pay large sums to have had at that time this book written by Major Hallows, for it explains not only the theory of radar in words which we can all understand, but the practice and development as far as we have gone to-day. Where radar will lead us to-morrow it is not easy to predict, but it is quite certain that this technique, which was developed largely for war purposes, will be the greatest possible boon in our normal life.

The author was Chief Instructor in A.A. fire control at one of our great A.A. Group Schools. As Chief Instructor he had to devise methods of training large numbers of A.T.S. and male operators in the theory of radar and in its use. As I read his book I could see why he had been such a successful Chief Instructor, for he has the gift of making extremely difficult and abstruse things appear simple and even obvious.

This book would have been of great value to us all in the war years, and to-day it will be welcomed by hosts of people who are interested in this new scientific development, which is only now in its infancy.

F. A. PILE,
General.

Preface to the Second Edition

AT the time when the first edition of this book was written both printing and binding were rendered slow processes by the prevailing shortage of labour. Many months might, therefore, elapse between the writing of a book and its appearance in print.

The manuscript of the first edition was finished in August 1945, but the book could not be published until the following April. During that interval of eight months the official attitude towards radar underwent a great change and it became permissible to speak of things which had previously been highly secret.

By the time that this had happened it was too late to make alterations in the first edition, in which it had to be stated in several places that detailed information about certain interesting aspects of radar could not be given for reasons of security.

There are still some applications of radar which are secret; but the relaxation which has taken place makes it possible in this second edition to give much information that had previously to be withheld.

Details are now given, for example, of the way in which an operator is enabled to measure range with a maximum error of 25 yards.

It is also possible to disclose what the operators measuring bearing and angle of sight see on the screens of their Cathode-ray tubes.

Chapters X, XI and XII have been largely rewritten and much has been added to Chapters XIV and XV. Chapters XVI and XVII describe in detail marine radar systems, and the magnetron valve. No more than a mention of either subject was possible in the first edition.

No book on radar can be final, for development is constantly taking place. But in this edition the gaps that had perforce to be left in the first have been filled in and the reader is given what is I hope and believe a good, clear picture of the basic principles of radar and of its most up-to-date developments.

R. W. HALLOWS.

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CHAPTER I

Introductory

THIS book is above all things simple. It contains no mathematics and calls for no previous knowledge of electricity in general or of wireless on the reader's part. During the war with Germany it was part of my job to teach radar to men and women—officers and other ranks—of Anti-Aircraft batteries. They came from all walks of life and very few indeed of them had ever in their lives tackled anything of the kind. I remember asking one class of twelve A.T.S. girls what their occupations had been in civil life: two were married women, who had done only domestic work, one had been a shop assistant, one a typist, one a cinema "usherette." Two clerks, a governess, a laundry hand, a bookkeeper, a university student and a dressmaker completed the tally. All of them became first-rate radar operators.

Methods of instruction intelligible to all had to be devised and it is largely upon these that this book is based. It is not written for scientists or for wireless experts, but for the ordinary man and woman, who will find nothing difficult to understand in the pages which follow.

My aim has been to give a clear picture in non-technical language of what radar is, what it does and how it works. I have made considerable use of analogies, for it is always easier to grasp an unfamiliar idea if a parallel to it can be found amongst familiar things. Few, if any, analogies are perfect. Most of them break down if they are stretched too far; but if they are carefully chosen they can often serve the useful purpose of clearing up points that might otherwise be difficult to understand.

Let me give an example. To many people who have read a little about radar the idea of sending out wireless waves, making them, so to speak, bounce off a distant aeroplane and return to their starting point is utterly uncanny. It is a process so mysterious that they simply cannot imagine how or why it takes place. Yet those same people find nothing either mysterious or uncanny in locating a lost collar stud in a dark corner with the aid of a pocket flashlamp. You switch on the flashlamp, they say; its light falls on the stud so of course you see it. What mystery could there possibly be about that?

And yet the two processes are exactly similar. The reason why the stud is seen is that light waves sent out by the flashlamp return from the stud and reach that marvellous instrument the eye, which is able to detect them. Wireless waves, as we shall see, belong to the same great family as light waves. They travel at the same speed and have many points of behaviour in common. But the eye cannot detect wireless waves, any more than a wireless receiving set can detect those of light.

The wireless waves of radar return from an aeroplane just as do those of a searchlight. The eye sees the plane because it detects the returning light waves. The radar receiver also "sees" the aeroplane because it detects the wireless waves that come back to it. Think of radar as bathing its targets in invisible illumination and the difficulty vanishes.

Radar was a war baby. Though it was born some little time before we were actually at war, it came into being because the trend of events from 1935 onwards made our government realise that sooner or later a fight for existence might be forced upon us and that some effective means of defence against air attacks was of paramount importance. Research was placed in the hands of a very able body of scientists and they were provided with ample funds for carrying on their work. But though radar was first developed as a weapon of war, it is going to give—in fact it is already giving—far greater service in time of peace. We shall discuss these peacetime functions in some detail; but before we can do so we must discover how radar was developed and how it works. To understand these things we shall have to begin with to regard radar as what it originally was—a weapon. Once its basic working principles have been made clear we shall go on to see how it has become one of the most valuable of means of saving life and ensuring safety in the days of peace.

The history of radar is a long one, for the underlying principle, the reflection of wireless waves by a target, has been known to science for many years and a good deal of use has been made of it for various purposes. Absurd claims have been made that this country or that was the birthplace of radar or that some particular man invented it. The truth is that nobody invented radar. It is a development of a well known principle and work upon it was going forward vigorously in both allied and enemy countries when the war broke out.

It is, though, one thing to know and understand a theory and quite another to evolve a sound working system based upon it. Without any question Britain was the first country in the world to develop an efficient, practical system of radar and to put it into operation. Those who visited the coastal districts of eastern and southern England during the years before the war were puzzled by the groups of tall lattice-work masts that sprang up in so many places. There were all kinds of quaint rumours about them. Not a few were convinced that they were concerned with some kind of death-ray, and there were tales of the sudden immobilisation of long lines of motor cars that had been passing near them.

Actually they are the aerial masts of radar stations. Alone of all the countries of the world we had a complete system of radar in operation when the war broke out. And it was well for us that we had. Some would go so far as to say that radar was the main factor in winning the war. However that may be, it is at all events certain that it saved us from losing it when we stood alone in 1940 and 1941.

Without radar we could not have won the Battle of Britain. I was at that time Senior Gun Control Officer for the A.A. batteries north of the Thames Estuary. How well do I remember the wonderful timely warnings of enemy attacks that we owed to the ever wakeful eyes of radar! Before the first of the great daylight raids a message came through: "H 1, hostile, 200 *plus*, circling to gain height over Amiens." There was then and all through those critical days ample warning of impending attack. We had plenty of time to man the guns. The Royal Air Force had plenty of time to send its small fighter force—the Few who did so much for so many—exactly where they were needed most. The civilians were able to take cover. The A.R.P. and Fire Fighting Services were ready to play their part.

Think what these early warnings, and the minute-by-minute reports of a raid's progress meant. We were able to plot its course on large scale maps and to see quickly whether or not it was likely to come within range of our guns. Both officers and men of the A.A. guns were working at terrific pressure and with very little rest. During the first period of the heavy air attacks that began in the summer of 1940 the main mass raids were made by daylight; but considerable numbers of enemy aircraft came in throughout the night as well. Later, daytime attacks on a grand scale ceased and great raids by night took their place. But that does not mean that all was quiet by day. Far from it: hostile planes were always coming in on reconnaissance or other missions.

You will realise that had it not been for the warnings of radar and the courses that it made it possible to plot, the gunners would have had no rest and that important parts of the defence scheme might well have broken down. Just how important was the part that the A.A. guns played in the Battle of Britain is not always realised. During the battle and the great night raids that followed it, the 6th A.A. Division covering the areas north and south of the Thames Estuary destroyed over 200 enemy aircraft for certain, with a much larger number probably destroyed or damaged. That could not have been done without the aid of radar, which enabled the men to be given some rest—though often it was little enough for days and nights on end. "Action" was ordered only when the radar instruments showed that a raid would come within range of the guns of a particular area. Very different are my A.A. memories of the 1914-1918 war when there was no such thing as radar. Then we would receive the message "Special Vigilance," usually at dusk, meaning that our ships had sighted Zeppelins over the North Sea. We stood to, with nothing but our ears to help us detect the approach of the enemy until, some ten or twelve hours later, "Special Vigilance Ended" came through.

In the Battle of Britain our fighter aeroplanes, very few in number, utterly routed the gigantic Luftwaffe. That could never have been accomplished without the warnings and the subsequent information given by radar. We had not the machines or the pilots to keep defensive patrols constantly in the air all round our east and south-east coasts. With the aid of radar fighter aeroplanes and fighter pilots could be kept on the ground until the moment for action came. Machines could be overhauled and repaired and pilots could snatch some sleep. Then when the warnings came the fighters could be concentrated just where they were most needed.

One of the most potent factors in warfare is surprise. Take your enemy by surprise, as we did in Normandy on D-Day, and you are half way towards defeating him. Britain, by having a radar system in being when the war broke out, made it impossible for the enemy to launch heavy surprise attacks from the air. On the other hand, we were able to surprise him by having our small force of fighters at the place where it could do him the most harm, our A.A. guns manned and our civil population warned when he attacked.

In a later chapter we shall see that this was by no means the whole of the aid that we received from radar. It became a powerful weapon at sea as well; and not only a defensive weapon, for radar helped the Navy to win some of its greatest victories. We shall see, too, how on the one hand it made night raiding so costly for the enemy that his attacks dwindled and finally ceased altogether, and on the other it enabled our Lancasters and Halifaxes to drop their bombs with deadly precision on targets obscured by cloud, fog or smoke-screens.

Very fortunately for us, the enemy made much slower progress in developing radar than we did. German scientists, like the rest of the scientific world, were well aware of the principles on which it is based long before 1939.

The Germans had working radar systems, but these were, both before and during the war, much inferior to our own. And what is more, we knew all about them. Soon after the outbreak of war our authorities received a communication, smuggled through a neutral country, from an anti-Nazi German. He offered to supply full information about existing German radar; if we wanted it, certain words were to be used in the B.B.C.'s European broadcasts. Those words were used and the information came through the same underground channels as the original communication.

In 1943 we wanted full details of German coastal radar stations. A Commando raid was made on one of these at Bonneval, near Dieppe, and with the raiders went one of the scientists who had done such splendid work in inventing and developing our radar appliances. He was able to make a thorough examination of the station, the most important working parts of which were removed and brought home by him and his assistants. His report, one of the most interesting and, at the time, one of the most secret documents of the war, gave a complete and detailed description of the whole apparatus.

The reason why the Germans were at all times a long way behind us in radar (and the same is true of the naval, military and air force applications of wireless) is this. They believed that the war would be over in two years and that the technical equipment which they possessed at its outbreak would be adequate for all requirements. On this account they closed down all research in wireless and radar in September 1939. When they realised their mistake and attempted to restart it they could not possibly make up the leeway.

We, on the other hand, mobilised our scientists before war came. Some of the finest brains in the country were allotted to radar and their efforts were intensified as the war went on. Hence we were always at least one jump ahead of our enemies in the technical field and that made our eventual victory certain.

Amongst the greatest triumphs of British radar is that the apparatus proved itself from the first able to withstand the rough handling and the exposure to all kinds of weather that must necessarily come its way in wartime. And ingenious devices made it so simple and straightforward to manipulate that after a comparatively short period of training, ordinary soldiers, and later girls of the A.T.S., became reliable and efficient operators.

So much, for the moment, for the history of radar and for what we owe to the foresight of the Navy, Army and Air Force in realising its possibilities and in seeing that the finest brains available were applied to developing it before we were forced into the grimmest struggle in our history. Now let us see what radar is, what it does and how it does it.

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CHAPTER II

What is Radar?

THE name radar was coined in the United States. From one point of view it is by no means so good as the original English term, radiolocation, which exactly describes the process: the *location* of objects by *radio*. Radar, Americans say, stands for *RA*dio *D*irection *A*nd *R*ange, which does not fully define the art, for, as we shall see later, direction and range alone are not sufficient for locating such a target as an aeroplane in flight. Radar, however, has the advantage of brevity, with its two syllables instead of the six of radiolocation, and largely for this reason it has come into general use. Actually it does become fully descriptive if we interpret it as meaning *R*adio *A*ngle *D*irection *A*nd *R*ange.

Radar is a very special kind of location by radio. It differs from all other methods in that the ship, the aeroplane or whatever we may wish to locate is not called on to take any active part in the proceedings. The crew, in fact, may be, and usually are, entirely unaware that the position of their craft is being measured and its course plotted by radar stations. In all other methods of location by wireless the "target" itself has to co-operate. To distinguish them from radar these other methods are usually known by the general name of DIRECTION FINDING (DF). It will be a help to understanding radar methods if we spend a little time in gaining a rough idea of how direction finding is done.

Anyone who has used a portable wireless set knows that to receive a particular broadcasting station at its best the cabinet must be turned in a certain direction. The cabinet contains what is called a frame aerial, which is really nothing more than a narrow coil of large diameter. Signals are at their strongest when the set is so turned that the windings of the frame aerial are on an imaginary line

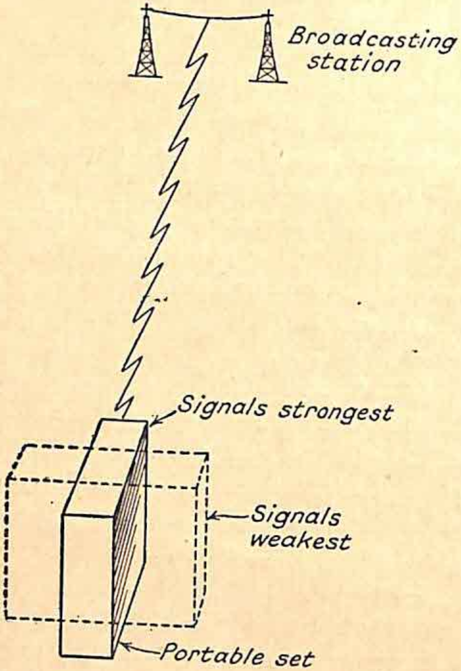

FIG II. 1.—Signals are strongest when a portable wireless receiver is turned so that its frame aerial points towards a broadcasting station. Turn the set through a right angle to the position shown by the dotted lines and signals are at their weakest.

joining the broadcasting station and the receiver. You will find, though, if you care to make the experiment illustrated in Fig. II. 1, that the position in which the station is most loudly heard is not very definite: you can turn the set some little distance one way or the other without there being any marked falling off in the strength. Now turn the set slowly away from the position at which the strength is greatest. There will be a point, and a much more definite one this time, where signals are very weak, or even disappear altogether. At this point, the ZERO POINT or MINIMUM, the windings of the frame are at right angles to the imaginary line joining set and broadcasting station. This is the basic principle of direction finding and the minimum is always used since it is so much more marked, or so much "sharper" than the MAXIMUM and therefore gives a far better indication of direction.

If you have a friend living some miles away who also has a portable set you can find the approximate position of a not very distant broadcasting station in this way. I say "approximate" because portable sets are not designed as direction-finding instruments and cannot be expected to give closely accurate indications. Find the minimum position with your set, then with a compass take the bearing exactly at right angles to the long sides of its cabinet. It is simplest to use a compass marked off in degrees right round the circle clockwise from 0 to 360 degrees (See Fig. XII. 1.). This bearing must now be converted into a "true" bearing, for, as you know, the compass needle does not point due north. The true bearing is found by subtracting from the compass bearing the DECLINATION of the needle, the correct figure for the year being found from a reference book, such as *Whitaker's Almanack*. Pinpoint your house on a map as nearly as you can and through it rule a pencil line on the true bearing that you have obtained. When the friend reports his bearing, mark his position on the map and rule in his line. If the work has been done carefully and there are no baleful influences causing either or both the sets to make considerable errors, the broadcasting station will lie at or near the point at which the two straight lines cross.

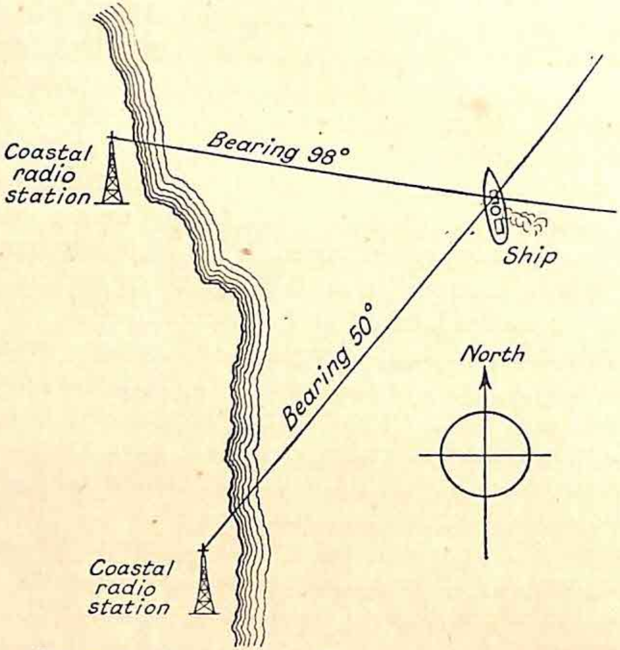

FIG. II. 2.—How two coastal wireless stations can find the position of a ship at sea.

Fig. II. 2 shows how a pair of coastal wireless stations equipped with accurate direction-finding gear can find the position of a ship at sea in this way. The ship sends out a radio signal and the stations each measure the bearing shown by the minimum strength position. The two bearings are plotted on a chart and the ship's position is seen at once. Here the "target" has taken an active part by sending out the wireless signal. Usually the ship finds her own position by making use of the radio beacons which are now in operation round the coasts of most civilised countries. These send out continually—you may have heard them without knowing what they were—their call-signs in morse, followed by a long drawn-out note lasting for many seconds. With direction-finding gear the navigator measures the bearings of two or more beacons, rules in the lines corresponding to them and sees his position clearly. The target's active part here consists in receiving the signals, measuring the bearings to the beacons and in ruling the corresponding lines.

The word "target" is most convenient for indicating the object—ship, aeroplane, town or whatever it may be—whose position is to be found. I shall use it throughout this book in that sense.

You will see that direction finding demands not only co-operation by the target, but also the use of at least two transmitting or receiving stations. It is a most valuable art and great use is made of it. No ship, for example, whose direction finding gear is in working order can ever remain in doubt about her position if she is within wireless receiving range of a civilised coast. Many an enemy surface ship and submarine has been spotted and subsequently sunk because her wirelessed reports enabled her position to be accurately determined. Our own heavy bombers, returning from raids on Germany, were guided in the early days of the war to their aerodromes by direction-finding systems and the same methods were used then to bring our fighters into contact with enemy raiders. The raiders were radiolocated, but direction-finding gear was used to determine the position of our fighters from moment to moment and by means of the wireless telephone the controller on the ground was able to order them to steer courses that would bring them into contact with the enemy.

The reason why two or more stations are needed for direction finding is that their instruments can measure bearing only and not range. To locate a target on the surface of the sea or on the ground by means of a single station it is necessary to determine not only in which direction it lies, but also exactly how far away it is. Given those particulars, the rest is simple. A line on the measured bearing is ruled on the map; then the measured range from the station is marked off on that line and there is the position of the target.

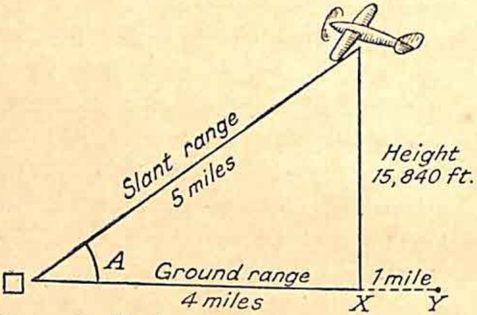

FIG. II. 3.—To locate an aeroplane we must know the height as well as the slant range. In this case the aeroplane, flying at 15,840 feet is immediately overhead of the point X, only 4 miles away on the ground. If we disregarded the height and used the slant range only we should plot its position at Y on the map—a whole mile too far away.

But even those two measurements are not sufficient to obtain the position of an aircraft flying above the surface of the earth. We want to be able to mark on the map the point which is vertically below the aeroplane. The surfaces of the ground and of the sea have only two dimensions; two measurements—latitude and longitude, or range and bearing—suffice to locate targets on them. But once we leave the surface and get up into the air a third dimension, height, is involved. Range-measuring instruments (including radar gear) determine the range along an imaginary straight line joining target and measuring apparatus. This (Fig. II. 3) is called the SLANT RANGE. Suppose that the target is flying at a height of 3 miles (15,840 feet) and that the slant range is 5 miles. As the drawing shows the target is immediately above the point X, which is only 4 miles away, and that is where the position should be plotted on the map. But if we disregarded the height altogether and took the slant range as being the same as the GROUND RANGE the plot would be made at Y and the indicated position of the target would be a whole mile out. We cannot plot X, the correct position, without knowing the height of the target.

Actually, radar does not measure the height directly. It gives direct measurements of the slant range, of the bearing and of the angle A, which is called the ANGLE OF SIGHT, or simply the ANGLE. If you know the slant range and the angle it is easy to find the height by means of trigonometry, but there is no need in practice to bother about trigonometry, for the calculation is always done automatically by ingenious instruments. Feed the slant range and the angle into them and they instantly tell you not only the height, but the ground range as well and you can mark the position on the map with no trouble at all.

Those then are the main differences between radar and direction finding. In direction finding two stations at least are required, since they measure bearing only and not range or angle. The target must play an active part and if it is an aircraft it must inform the ground stations of the height at which it is flying before its position can be determined accurately. On the other hand a single radar station can find the exact position of a target at sea, or in the air, without the target's doing anything at all. You could not locate an enemy plane by direction finding methods unless its pilot was obliging enough to send out wireless signals, you could not plot its course on a map unless he kept on sending them—and in any event your plots and your course would be incorrect unless the pilot still more obligingly told you the height at which he was flying. Radar enables all of these things to be done and the pilot is more than likely to be completely unaware that anything of the kind is happening to him and his aircraft.

There are many types of radar instruments. All work on the same broad lines that we are about to investigate, but they may be divided into two main classes. Earlier instruments provided only a moderate degree of accuracy. They could measure the range of a target to within about 25 yards up to 8-10 miles; but their measurements of angle and bearing were none too good. The later precision types of radar provide very accurate measurements of range, angle and bearing. Radar of the first kind is still used to some extent when the approximate location of targets at great range is all that is needed. But it is being replaced rapidly by precision radar apparatus, which furnishes not approximate but exact data.

CHAPTER III

Measuring Ranges by Sound Echo

ALL the sounds that we hear are due to waves which travel through the air. They are not quite like the familiar water waves, for they travel not over the surface of the air, but through it—and they are, of course, invisible. When the string of a piano is struck by its hammer it vibrates and the rapidity with which it vibrates depends upon its length, its heaviness and its tautness. When the piano tuner goes to work with his key on the middle C string he tightens or loosens it until it vibrates some 256 times a second when struck; his ear and yours then hear the sound which we know as middle C.

Fig. III. I shows diagrammatically what happens during one vibration of the string. At (*a*) it has moved to the right, compressing the air that lies in its path. At (*b*) it has swung in the opposite direction, leaving a patch of rarefied air behind it. And so at the end of one vibration it has produced a disturbance in the air consisting of a high-pressure area, which we may call the CREST of the wave, followed by a TROUGH of low pressure. These alternate crests and troughs travel outwards, there being one crest and one trough—or one complete wave—for each vibration of the string. On reaching the ear the high-pressure crest presses the eardrum inwards and the succeeding low-pressure trough makes it move outwards. Thus each to-and-fro movement or vibration of the string causes a corresponding movement of the eardrum. If the string

vibrates at a frequency of 256 a second, the eardrum vibrates at the same frequency and the sound of middle C is heard.

The speed at which sound waves travel through the air

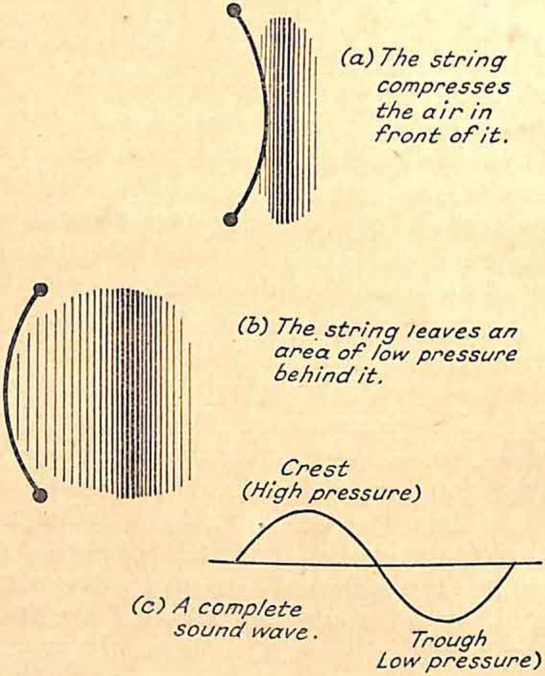
(a) The string compresses the air in front of it.
(b) The string leaves an area of low pressure behind it.
Crest (High pressure)
(c) A complete sound wave.
Trough Low pressure)

Fig. iii. 1.—Showing diagrammatically how a vibrating string produces sound waves in air.

varies with climatic conditions; but a round average figure is 1,120 feet a second. It you are standing 1,120 feet from a gun when it is fired, just one second will elapse between your seeing the flash and hearing the sound of the explosion. In warfare practical use is made of a variation of this principle in the process known as

SOUND RANGING. This depends not on seeing the flash and timing the interval between it and the arrival of the sound, but on recording very accurately the instant at which the sound reaches each of a number of observing posts whose positions have been carefully determined by survey methods. This done, it is possible, by methods into the details of which it is not necessary to enter here, to ascertain the precise position of an enemy gun. A further elaboration of sound ranging is to use it for locating the burst of your own shells directed against the enemy gun. By ordering corrections until the bursts occur at the exact point at which the hostile gun has been located it may be put out of action without its having ever been seen by either gunners or observers.

You will notice that the process of finding the range by seeing the flash and timing the arrival of the sound as well as that of sound ranging bear some relation to direction finding by wireless: in both the target must take an active part. In direction finding it either sends out a radio signal, or plots the bearings on which signals from radio beacons are received; in sound ranging the target must give rise to a noise that can be heard by the ears or detected by the instruments of those who wish to discover its position. But sound waves may also be used to find the range of a target which does nothing more active than act as a reflector and send them back to their source as an echo.

Suppose that you are standing as in Fig. III. 2 on a flat piece of open land, on which there is a house some distance away. You shout "Hi!" and a little later an answering "Hi!" makes itself heard. You recognise the answering "Hi!" as an echo and decide that the house must be acting as the sound reflector and causing it. Can you find, without moving from where you are, just how far away that house is? Certainly you can if you have a stopwatch. Shout again, starting the watch as you do so, and stop it when you hear the returning sound.

The measured time is, let us say, six seconds. In six seconds sound waves travel six times 1,120 feet, or twice 1,120 yards. What, then, is the range? Quite possibly you were just going to say 2,240 yards; but is it? It is true that the sound waves have travelled that distance, but that includes both their outward journey from you to the house and their homeward journey from the house to you. The range, the distance between you and the house, is not this double journey, but just half of it. In the example illustrated in Fig. III. 2 the six seconds timed by the stopwatch represent a range not of six times, but of *three* times 1,120 feet, that is, 1,120 yards. If, then, we are going to do our ranging by means of sound echoes, each second on the stopwatch will represent 1,120 feet of wave travel, but only 560 feet of range. That is the important

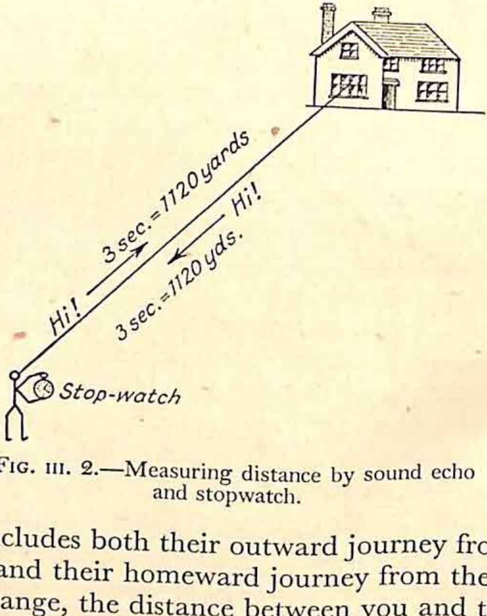

FIG. III. 2.—Measuring distance by sound echo and stopwatch.

principle of any kind of echo-ranging: the waves make the double journey to and from the target and the range is equal to one half of the whole distance travelled.

Practical use is made of this method of echo-ranging in deep-sea sounding. Sounding waters like those of the Atlantic and the Pacific Oceans, which are several miles deep in places, used to be a slow and laborious business when it was done by means of the deep-sea lead, lowered on a fine steel wire from the surveying vessel. To obtain accurate measurements the ship had to move at dead-slow speed or to stop altogether in order to avoid the lead's lagging behind and the length of the wire paid out indicating what, remembering the slant range of Chapter II, we may call the "slant depth," which might be considerably greater than the true measurement. And even with the help of machinery it takes a considerable time to lower the deep-sea lead five miles, or to wind it up again.

The modern survey ship, equipped with echo-sounding devices, is troubled by none of these things. She measures depths in the way shown in Fig. III. 3. A short train of sound waves sent out by the ship reaches the sea bed and is reflected back. Timing gear on board measures the time, automatically converts it into depth and records it. The speed of sound waves through sea water is much greater than that through air. There is therefore comparatively little slant effect, except in very deep waters, and what there is can, if necessary, be allowed for and eliminated so long as the ship's speed is constant. She can steam ahead at a good speed whilst her echo-sounding instruments automatically measure the depths over which she passes and draw a contour picture of the sea bottom below like that drawn by the stylus of a barograph, or recording barometer.

An interesting new use has been found for echo sounding equipment. It was noticed that in addition to the well-defined lines which depict the contours of the sea-bed, other lines, considerably fainter, appeared on the record paper. These lines were always some distance above the bottom and investigation showed that they were caused by echoes from shoals of fish. Many drifters and trawlers are now using ex-naval echo sounding apparatus for locating shoals of herrings and other fish. This "fishing by radar" (for that is what it amounts to) is finding increasing favour with deep-sea fishermen and it is not unlikely that apparatus specially designed for the purpose will be developed.

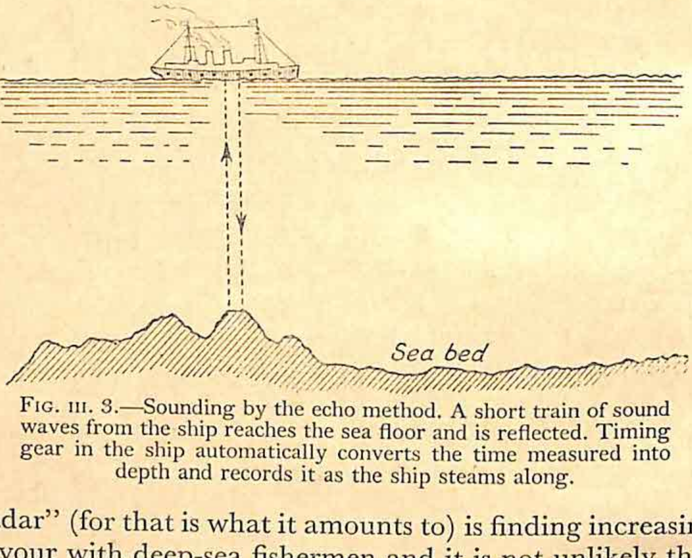

FIG. III. 3.—Sounding by the echo method. A short train of sound waves from the ship reaches the sea floor and is reflected. Timing gear in the ship automatically converts the time measured into depth and records it as the ship steams along.

Finding range by means of sound-wave echoes clearly has some very useful applications; but it has also its limitations, and the most important of these is due to the comparatively small speed at which sound waves travel. A speed of 1,120 feet a second may not at first sight seem exactly low. Translated into miles an hour it works out a little over 760 m.p.h., which is fairly fast moving in view of what we can accomplish by most mechanical methods. But it is not particularly rapid in comparison with the speed of aeroplanes.

When the war broke out in 1939, bombers were capable of travelling at 180-240 miles an hour and fighters topped the 300 m.p.h. mark. To-day, these speeds have been enormously exceeded. Jet-propelled aircraft already travel at something approaching the speed of sound.

But, leaving aside the speeds which aircraft have reached to-day, let us send our thoughts back to the beginning of the war and see whether there could have been any hope of applying successfully the methods of ranging by sound echo to the location of enemy bombers on their way to this country. In those days the average speed of an approaching raider was about 200 miles an hour.

Imagine that we have devised some means of producing a sound echo from a distant plane and of detecting it. An enemy bomber is, we will take it, 20 miles away and coming straight towards us at 200 m.p.h. when we send out the ranging sound. The aeroplane will have travelled just over four miles by the time that the sound reaches it and more than eight miles by the time that the echo returns to our detecting gear. Not only should we receive our information very late—the bomber would be under 12 miles away when we got it—but we should be measuring the range not to where the aircraft *is* but where it was; and if you want to succeed in shooting down hostile aeroplanes, it is not very helpful to know what the range was some time before the guns are fired. Anti-aircraft gunfire can achieve its object only if the actual range can be obtained from moment to moment. Then that remarkable instrument, the predictor, can foretell accurately what it will be by the time that the shells have made their upward flight, and ensure that their fuzes are set so that the bursts will occur when shells and target arrive at the same point.

Sound waves are clearly too slow to answer the purpose of finding the range of a distant aircraft by the echo method; but the echo method is the only one that will answer, for obviously the hostile pilot is not going to help by sending out wireless signals. He knows only too well how they would assist those who seek to destroy him. The answer to the problem is found by using wireless waves to cause the echo and by timing their journey to and from the target. The speed of wireless waves is about a million times as great as that of sound waves and we shall see how they enable us to find not the past but the present range of a fast-moving target at any moment. The anti-aircraft predictor requires not only up-to-the-moment ranges, but also bearings and heights. Making use of wireless echoes, radar supplies all these data.

Sound waves answer well in the case of stationary targets, as we have seen in sound ranging on guns firing from fixed positions. But when it comes to fast-moving unseen targets we can find instantaneous ranges only by harnessing to our service waves which travel at the highest speed attainable by any known thing in the universe.

CHAPTER IV

Ether Waves

BESIDES the waves that travel through air and give rise to the sensation of sound there is a whole great family of waves which affect us in our everyday lives. These are the ETHER WAVES, or ELECTRO-MAGNETIC WAVES, all of which have certain qualities in common. All, for example, travel through the medium known as the ether and all move at the same tremendous speed. Just what the ether is presents a problem that has been the subject of scientific controversies for many years. This is not the place to enter into any kind of discussion of the matter and it will be sufficient for our purposes if we take it that the ether is an invisible, intangible medium, which pervades not only the whole vast realms of Space, but also every chink and cranny of the matter of which men and rocks, gases and liquids, metals, plants and all other substances are composed. Through it travel the electro-magnetic waves and, unlike those of sound, their speed is fixed and unvarying.

The only way in which the many kinds of electro-magnetic waves differ from one another in their nature is in their length. The effects which they produce are of very considerable variety; but the sole reason why one set of these waves gives rise to, say, the sensation of light and another set to the sensation of heat is that the former are shorter than the latter.

And now, perhaps, we had better see just what is meant by the length of a wave. You know that when you use a wireless set, one broadcasting station may be found if you tune to 1,500 metres, another at 460 metres, and so on; those are the WAVELENGTHS of the stations concerned. But what exactly is a wavelength? We saw in Chapter III that a sound wave consisted of an area of high pressure, followed by an area of low pressure. The pressure rises from normal to a maximum, which we call the crest (see Fig. III. 1), falls back to normal, then drops to the trough of lowest pressure. Ether waves also have their crests and troughs, which may be regarded as the points where stresses and strains in the ether are greatest first in one direction and then in the other.

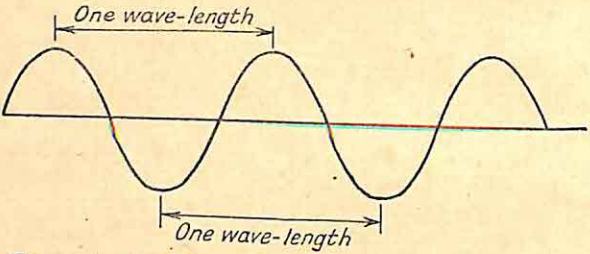

FIG. IV. 1.—The length of a wave in the distance, usually measured in metres or fractions of a metre, between any two consecutive crests or troughs.

The length of the longer ether waves is measured in metres or fractions of a metre. It is (Fig. IV. 1) the distance between any two consecutive crests or troughs. We shall have to use metres, rather than yards or feet or inches, a good deal in discussing radar, so it may be as well to realise just what a metre is. The metric system is in use in a great many countries outside our own and it is widely employed by scientists because its standards are understood by their fellow workers in all parts of the world. The metre is the unit of the measurement of length in this system. We can conveniently take it as a yard and a tenth, or a yard *plus* ten per cent. Thus ten metres are approximately equal to 11 yards, 400 metres to 440 yards and so on. In the metric system 1,000 metres make one kilometre, approximately equal to five-eighths of a mile, or five furlongs. (You will see that the yard-plus-ten-per-cent. rule works well: 1,000 metres = 1,000 plus 100 yards = 1,100 yards or five furlongs.) Each metre is divided into 100 centimetres and each centimetre into 10 millimetres. Approximately two and a half centimetres go to the inch, or 30 to the foot. A millimetre is about a twenty-fifth of an inch. You can amuse yourself by working out on these lines what sizes you would have to ask for it you were buying collars or a waistbelt on the Continent, where the metric system is in general use!

Hitherto we have rather assumed that light travelled from place to place in no time at all. Is it, in fact, true to say, as we said in Chapter III, that if you saw the flash of a gun and heard the report exactly one second later, the distance between you and the gun would be just 1,120 feet? As a matter of fact it is not, for light waves, like those of sound, take a definite and measurable time to travel from any one point to any other. Actually they would need a little over a millionth of a second to cover the 1,120 feet.

It probably never entered the heads of the ancient philosophers that the passage of light from an object to the eye took any time at all. But as learning progressed it was realised that there must be a delay, however small, between the time when an event took place and the time when it was seen and recorded by an eye some distance away. There were no means of measuring this delay (and therefore of determining the speed of light) until comparatively recent times, when the telescope had been invented and was in use by astronomers for observing the heavenly bodies. It was then found that the great planet Jupiter had a number of moons, and these appeared to behave in a rather curious way.

Every year the Earth travels round the sun in its orbit, the average distance between the two being about 93,000,000 miles. Round the sun in a vastly larger orbit and in a much longer time also revolves Jupiter. When the Earth was in the position E_1 in Fig. IV. 2 and Jupiter

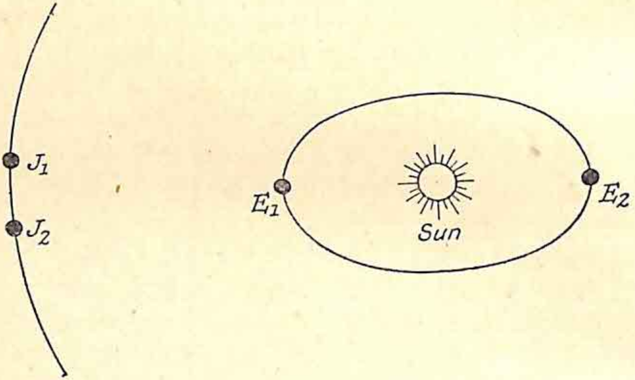

FIG. IV. 2.—Illustrating the way in which the speed of light was first measured. The drawing is not to scale. If it were so Jupiter's orbit would be off the page altogether.

at J_1 the time taken by one of his satellites to go round the big planet was accurately measured: it was visible for a certain period, then disappeared as it passed behind Jupiter, then made a re-appearance at his edge. As the Earth travelled farther and farther away from Jupiter towards the position E_2, the satellite appeared to be longer and longer about its revolution, until when E_2 was reached its re-appearance was some 16 minutes 40 seconds, or 1,000 seconds late. Owing to the enormous size of his orbit, the position of Jupiter in relation to the Sun had not changed very greatly. When the Earth was at E_2, he had arrived at J_2. As the Earth continued in its orbit from E_2 and drew nearer and nearer to Jupiter, the satellite under observation appeared to be less and less late in making its re-appearance and when the two planets were at their closest the satellite conformed to the original time measurements.

What was happening? Clearly the satellite could not be slowing down and speeding up as the Earth moved away from or towards it. The only logical inference was that it re-appeared 1,000 seconds late when the Earth was at E_2 because light from it took 1,000 seconds longer to reach E_2 than E_1. At E_2 the Earth was twice 93,000,000 miles, or 186,000,000 miles farther away than at E_1. Therefore light travelled 186,000,000 miles in 1,000 seconds, or 186,000 miles in one second.

When accurate methods of measuring the speed of light became available it was found that this estimate needed little correction and the speed of light is to-day taken in round figures as 186,000 miles a second. As we are going to think a good deal in metres in discussing radar, the equivalent speed in metres is worth remembering. This—again in round figures—is 300,000,000 metres a second. And that is the speed at which in all circumstances all ether waves travel. They are, for all practical radar purposes, completely unaffected by temperature, barometric pressure, darkness, daylight or weather conditions.

Ether waves are often measured not by their length, but by their FREQUENCY. The frequency is the number of times that a complete wave, consisting of crest and trough, occurs in one second. In technical language a complete wave is known as a CYCLE. Now look at Fig. IV. 3, which shows the head of a train of ether waves, each 1,000 metres long, arrived at point *A*. As their speed is 300,000,000 metres a second, the leading wave will have reached *B* one second later. Since each complete wave occupies in this instance 1,000 metres, it will be clear that when one second has elapsed from the moment shown in the drawing 300,000 complete waves will fill the space between *A* and *B*. In other words, when the wavelength is 1,000 metres, 300,000 complete waves or cycles occur in one second and the frequency is 300,000 cycles per second. A little thought will show that the frequency depends upon the wavelength and, *vice versa*, the wavelength upon the frequency. If we know one we can find the other by the simple process of dividing it into 300,000,000. Thus, if the wavelength is 50 metres, the frequency is 300,000,000 divided by 50, or 6,000,000 cycles. Similarly, if we know that the frequency is 10,000,000 cycles per second, the wavelength must be 300,000,000 divided by 10,000,000, or 30 metres.

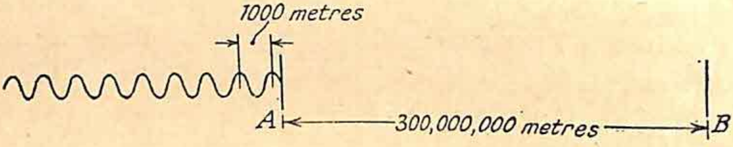

FIG. IV. 3.—The first of a train of ether waves, each 1,000 metres long, has reached point *A*. One second later the first wave will have travelled 300,000,000 metres to point *B*. How many complete waves will then lie between *A* and *B*? The answer is clearly 300,000,000 divided by 1,000, or 300,000.

For the sake of convenience we do not usually speak of a frequency of 40,000 cycles; we call it 40 kilocycles per second, the prefix "kilo" standing for thousand. In the same way "mega-" stands for million, and a frequency of three megacycles means 3,000,000 cycles a second.

So much for the terms wavelength and frequency. Now let us suppose that we have an apparatus which can be made to send out electro-magnetic waves of any length, the wavelength being controllable by moving a knob. We will start by making it send out very long (or low frequency) waves several kilometres, or thousands of metres in length. None of our senses can discover that anything is taking place. No matter for how long the waves are sent out or what power is behind them, they mean nothing to our eyes or ears or nerves. But if we bring a wireless set into action and tune it correctly, the set will detect the presence of wireless waves. Reduce the wavelength (or raise the frequency) steadily until the waves drop from kilometres to metres and presently centimetres and millimetres (thousandths of a metre) in length: our senses still make no response, though a properly tuned wireless set does. So far the ether waves are those we know as wireless waves.

Continue the reduction in wavelength. The wireless set presently throws in its hand and ceases to respond. But as the shortening of the wavelength continues we begin to be conscious of a sensation. The surface nerves of the body detect heat, which grows more and more intense as we proceed with the shortening of the waves, now only a minute fraction of an inch in length. As our movement of the knob makes the wavelengths still shorter we become aware of a fresh sensation; the eyes detect a dull red glow and as the shortening continues this becomes bright red, then orange, then yellow, then green, then blue, then indigo, then violet. A further shortening of the waves and the eye ceases to act as a detector; but the camera can "see" and take pictures in conditions where the eye would say that complete darkness existed—that is when the waves are too long (infra-red) or too short (ultra-violet) to produce any response in the eye. Shorter than the ultra-violet are X-rays and far shorter than the shortest of these are the "gamma" rays, which can penetrate many feet of solid lead.

All of these are ether waves. To sum up: all travel through the ether and at the same enormous speed; the different effects which they produce depend entirely upon their length; no one apparatus can detect all kinds of ether waves; the radio receiver detects wireless waves, to which the eye is blind; there are various kinds of light waves, invisible to the eye, whose presence the photographic plate detects. In radar we bathe the target in the invisible illumination of ultra-short wireless waves and make use of a special kind of wireless receiver to "see" it, to measure its slant range and to furnish the other data necessary to locate it exactly. We shall discuss the measurement of range first of all, for, once a means of doing this accurately has been found, the first great problem of radar has been solved.

CHAPTER V

Wireless Echoes

As was mentioned in Chapter III, radar measures its slant ranges by means of wireless waves which go out from a transmitter, meet the target and return to a receiver. To a good many people there is one rather puzzling point here. Keeping in mind, they say, the idea of the illumination of the target by invisible light and the analogy with the beam of the searchlight, we still cannot see why wireless waves should return to the place from which they were sent out. If the target—aeroplane or ship—had a perfectly smooth and even surface, we could understand its sending back wireless waves, just as a mirror sends back light waves. But the targets of radar, with their wings, their engines, their propellers and their tail fins, or their funnels, their masts, their turrets and their superstructures, have surfaces that are far from smooth and even and they consist of materials of many different kinds. How on earth, then, can any reflection of wireless waves take place from them? Perhaps we had better clear up that difficulty right away.

Radar uses very short wireless waves. The wavelengths employed by early types of radar equipment ranged from about 4 to 10 metres. Modern radar makes use of still shorter waves, with lengths of 1 to 10 centimetres. It is possible that the wavelengths of radar apparatus of the future will be measured in millimetres. These wireless waves behave in a good many ways like those of light.

When light waves pass from one medium, such as air, into another of a different kind their path is diverted or bent. You can see that by putting some inches of a walking stick into clear water and viewing it from various points:

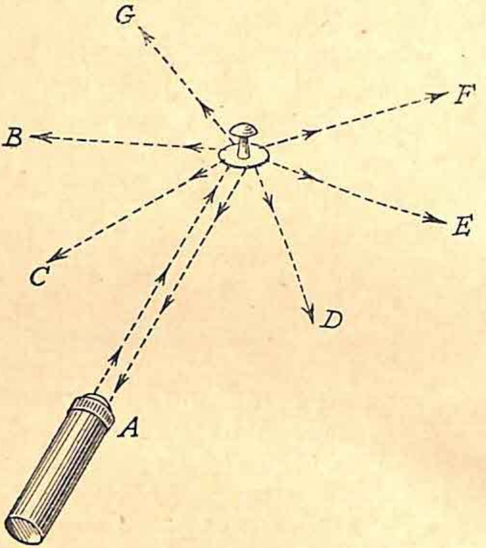

Fig. v. 1.—Light waves reaching an irregular surface are scattered—bent in many directions. Thus light from a flashlamp falling on a missing collar stud returns in part to its source; but it also goes out in various directions, making the stud visible at *B*, *C*, *D*, *E*, *F*, and *G*, as well as at *A*.

the stick appears to be bent sharply at the place where it enters the water and the immersed part seems to be in a position which it could not possibly occupy in reality. It is not, of course, the stick which bends, but the rays of light reaching and leaving its submerged part which are bent or refracted as they pass from air to water or from water to air.

If light waves meet a suitable smooth surface, such as that of a mirror, lying at right angles to their path, they are bent right round and reflected back. But if the object which they meet has an irregular surface, as when the missing collar stud of Chapter I is lit up by the beam of a flashlamp, Fig. v. 1 the waves are SCATTERED or bent in many directions. Some part of the light is reflected back to its starting point and your eye, if placed quite close to the torch, sees the stud. But if the torch is left where it is and you move to various places, the light waves, scattered in many directions, enable the stud still to be seen.

Very short wireless waves are bent and scattered in very much the same way by an uneven surface such as that of a radar target. Fig. v. 2 gives some idea of what happens when those from a transmitter *T* reach a distant aeroplane. Scattering occurs, but part of the radiation is sent back to the receiver *R*. It may be only a very small part, but if the receiver is sensitive enough and is able to amplify the tiny returning signal sufficiently, it will be detected and can be magnified until it becomes a useful radio echo, making it possible to measure the distance to the target.

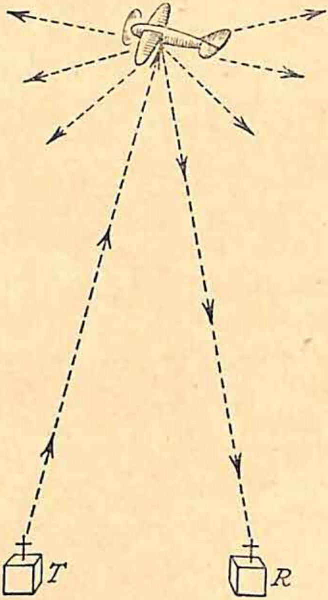

FIG. V. 2.—Short wireless waves from a transmitter *T* are also scattered on reaching such a target as an aeroplane. But a small part of the radiation comes back to the receiver *R*.

As with the sound echoes discussed in Chapter III, the time taken by the wireless wave to travel from transmitter to target and back to receiver has to be measured. If we can find a means of doing this accurately we shall be able to measure ranges at all times and in all circumstances, for the speed of wireless waves is fixed and unvarying. Whether it is hot or cold, light or dark, clear or foggy that speed remains constant. But it is a very high speed indeed and the problem of measuring the travel times of wireless echoes seems to be rather a formidable one.

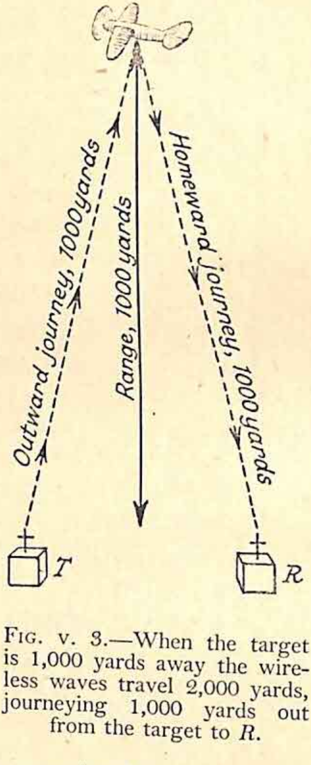

FIG. V. 3.—When the target is 1,000 yards away the wireless waves travel 2,000 yards, journeying 1,000 yards out from the target to *R*.

We have already seen that in round figures the speed of wireless waves is 186,000 miles, or 300,000,000 metres a second. A glance at Fig. V. 3 reminds us that the distance travelled by the waves is twice the range. They journey outwards from the transmitter *T* a distance equal to the range, then come back as an echo from the target over the same distance to the receiver *R*. Now suppose that we are using long-range radar equipment and that the target is 93 miles away. Since the waves travel at 186,000 miles a second they will make the return journey of 93 + 93 = 186 miles in one-thousandth part of a second. To range on a target just over 9 miles away we must be able to measure an interval as short as one ten-thousandth of a second. But even 9 miles is a fairly long range and we find that if we want to obtain, as we must, ranges long and short we must somehow contrive a means of measuring accurately intervals as short as a fraction of a millionth of a second.

No kind of stopwatch could do it. The best of these can do no better than record tenths of seconds. In fact no mechanical appliance is going to be of any use to us at all. The chief reason for this is that such appliances must contain moving parts made of solid matter such as metal.

Spend a moment or two in watching the action of the balance wheel of a watch swinging to and fro on its pivot. It makes first part of a revolution in one direction, then part of a revolution in the other. Think, though, what is happening at each swing. Starting from rest, the wheel must gather speed, move through part of a complete turn, slow down, stop and then repeat the process in the opposite direction. Now everything which has weight or mass possesses two other properties: INERTIA, which makes it resist being set in motion when it is at rest, and MOMENTUM, which makes it resist any change in its speed once it is in motion. Twice in every complete swing the balance wheel fights, so to speak, against being made to start moving; twice it fights against being stopped when it is moving. The result is that there is a definite limit to the rate at which it can be made to perform its swings. Inertia and momentum mean slight delays in starting and stopping and we cannot afford to have even the smallest delays when we want to make measurements involving such tiny time intervals as millionths of seconds. These two qualities, in fact, rule out mechanical devices. To make such measurements we shall have to find something that can be made to stop and start without any appreciable delays and as many hundreds or thousands of times a second as we want. Just as we had to employ ether waves, whose speed is the highest known in the Universe, to give the rapidity of travel needed for echoes from fast moving targets, so to measure the time taken by those waves to make their out and home journey we must harness to our service what, so far as our knowledge goes, are the tiniest things in the universe. These are the ELECTRONS. By using them we can get rid, to all intents and purposes, of the handicaps of inertia and momentum and devise apparatus which will enable us to measure time intervals of almost incredible shortness.

CHAPTER VI

Something about Electrons*

THE best part of twenty-five centuries ago men of learning in Greece were doing some hard thinking about the constitution of matter—the things that we can touch and feel and see. One of their philosophers named Democritus put forward what was then an astounding theory. He held that it was possible to subdivide any kind of matter into the ultimate small particles of which it was built up. Suppose, for example, that you took a small piece of gold and cut it into halves, throwing away one of the portions and retaining the other; you could, he held, continue the process only up to a certain point. You halved the piece that was left after the first cut, discarded one half and then cut the remainder in two. You might go on doing this for quite a long time, but eventually you would come down to something so small that it was impossible to divide it further. That, he contended, was the ultimate small constituent of any mass of gold. He called it the ATOM, which means "un-cuttable."

In other words gold could be divided only into minute pieces of gold, zinc into minute pieces of zinc and so on. You could not go any further than that. Though it had its opponents, this belief was the nearest approach to the truth of the matter that was to be made by scientists for more than two thousand years. Substances were later divided into elements like gold or iron, made up of one kind of atom only, and compounds such as water which were found to consist of MOLECULES or groups of atoms; a water molecule is made up of two atoms of hydrogen and one of oxygen closely bound together.

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* For the sake of simplicity this account of the nature of the atom deliberately adopts the original Rutherford conception and avoids any mention of the neutron or of isotopes. Readers who wish to go more deeply into the atomic theory are referred to the author's "*Atoms and Atomic Energy.*"

Not until the closing years of the last century was it proved that the atom was very far from being the ultimate small particle, incapable of further division. It is true that a mass of pure gold consists of gold atoms only; but each gold atom is found to have nearly 300 constituent parts. The simplest atom, that of hydrogen, has two components, the next simplest, helium, has eight, and there are many atoms which are composed of hundreds of minute bodies. But all of these bodies, however simple or complex the atom may be, are of two kinds only. In other words, only two sorts of almost unimaginably tiny bricks build up the structure of each and every kind of matter ultimately; the nature of any particular piece of matter depends on the number and arrangement of the two kinds of little bricks of which it is composed.

The two sorts of bricks are ELECTRONS and PROTONS. Electrons may be regarded as minute charges of negative electricity and protons as exactly equal charges of positive electricity. That is to say, the positive charge of a proton $(+1)$ just cancels out the negative charge of an electron (-1): $1 - 1 = 0$.

The simplest of all atoms, that of hydrogen (Fig. VI. 1) consists of one electron and one proton. The electron revolves in an orbit round the vastly heavier proton very much as the earth revolves round the sun. Other atoms are a good deal more complicated. The composition of the helium atom, the next simplest to hydrogen, is shown diagrammatically in Fig. VI. 2. Here there is a central body, called the nucleus, consisting of four protons and two electrons, round which revolve a further two electrons. The oxygen atom has a nucleus of sixteen protons and eight electrons, with another eight electrons orbiting round it. Atoms may combine to form a molecule. As we have seen, each molecule of water consists of two atoms of hydrogen and one of oxygen in close association.

It is rather important to grasp that the total electric charge of any atom in a normal, balanced condition adds up to nought. Thus the hydrogen atom has one proton (+ 1) and one electron (− 1) and the sum is 0.

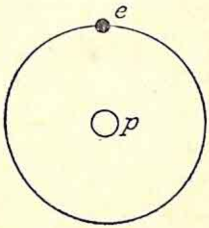

FIG. VI. 1.—The simplest of all atoms is that of hydrogen. Here one electron moves in an orbit round a single proton.

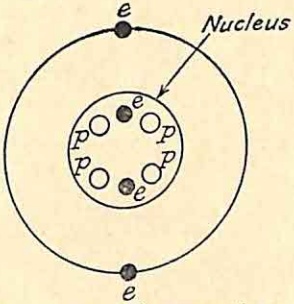

FIG. VI. 2.—Diagrammatic representation of a helium atom: *p*, *p* protons; *e*, *e* electrons.

The other atoms have nuclei built up of protons and electrons. The protons in the nucleus are always more numerous than the electrons; we have seen, for example, that in the nucleus of the oxygen atom there are sixteen protons and eight electrons. The electrical "balance sheet" for the oxygen nucleus is:

16 protons . . .	+ 16 units
8 electrons . . .	− 8 units
Total . . .	+ 8 units

The nucleus of the oxygen atom has thus a positive charge of eight units. When the atom is in a stable condition this is exactly cancelled out by the negative charges of the orbiting electrons. For the complete oxygen atom the balance sheet reads:

Nucleus	+ 8 units
Orbiting electrons . .	− 8 units
Total . . .	0

Atoms of different kinds have larger or smaller positive charges on their nuclei: that of the helium nucleus (Fig. VI, 2) is + 2, that of iron + 26, that of zinc + 30 and that of silver + 47. The very complex nucleus of uranium, used in the atomic bomb, has a positive charge of 92 units. But whatever the atom may be, the positive charge of the nucleus is normally exactly counterbalanced by the negative charges of the orbiting electrons. The two orbiting electrons of helium cancel the two positive units of the charge of its nucleus; and it is the same with the 26 orbiting electrons of iron, the 30 of zinc, the 47 of silver and the 92 of uranium.

Normally then, the atom has no electric charge at all: it is neither positive nor negative, but neutral.

But an atom may suffer the temporary loss or gain of one or more orbiting electrons. Its balance is then upset and it has a charge. Whether that charge is positive or negative depends on whether electrons are lost or gained. When, for instance, an accumulator battery is in use the temporary gain of an electron happens to millions upon millions of oxygen atoms in every second. With its extra orbiting electron each atom has this balance sheet:

Nucleus	+ 8 units
Orbiting electrons . .	− 9 units
Total charge . .	− 1 unit

In this state each oxygen atom has a negative electric charge. A point well worth remembering is that an electron surplus means a negative electric charge.

When the switch of a pocket flashlamp is pressed millions upon millions of zinc atoms in every second suffer the temporary loss of two electrons apiece. Again the balance is upset, but this time it is:

Nucleus	+ 30 units
Orbiting electrons	− 28 units
Total charge	+ 2 units

The zinc atom in this condition has therefore a double positive charge because it is short of two electrons. Again it is worth while to remember that a positive charge is due to a deficiency of electrons.

To sum up, a neutral atom has a number of negative orbiting electrons exactly equal to the units of the positive charge of the nucleus. The two sorts of electric charge exactly cancel one another out, with the result that such an atom has no electric charge. An atom which has gained an electron is no longer perfectly balanced. It has one extra negative charge and so is itself negatively charged electrically: an electron surplus means a negative charge.

If an atom loses an electron its balance is again upset. This time the units of the positive charge of the nucleus outnumber the negative orbiting electrons and the atom is positively charged: an electron deficiency means a positive charge.

So much for what positive and negative charges of electricity are. The next thing to discuss is how they behave. Dissimilar charges attract each other with a force vastly greater than that of gravity. No doubt you have had at one time or another a practical illustration of the force of gravity by dropping inadvertently something heavy on to a toe; you know therefore how strong a force it is. If you hold a pound weight at shoulder height and release it, it falls to the ground because the Earth and the weight attract each other. As the weight is millions of times lighter than the Earth it is the weight which makes a perceptible movement.

The proton is nearly two thousand times as heavy as the electron; hence, though each attracts the other, it is the electron which does most of the moving when this attraction takes place. An electric current is simply a stream of electrons. Think of the battery which you put into your flashlamp. On the positive pole (short brass strip or little brass cap) is an electron deficiency; the negative pole (long brass strip or the zinc can of a cell) on the other hand has a big surplus of electrons. So long as there is no conducting path between the two poles, nothing happens; but as soon as you press the switch a path is provided through the filament of the bulb. Swarms of electrons rush along this path towards the attracting protons. Such is the press of traffic that the filament is heated, glows and gives out light.

Unlike charges, then, attract one another with immense force; but like charges repel each other with a force that is equally great. Thus two electrons or two protons or any two bodies with similar charges strive to drive each other away.

In a word, unlike charges attract one another; like charges repel one another, the force in each case being far stronger than that of gravity.

Can we, I wonder, form any idea of the minute size of the electron? If you were asked what was inside the bulb of an electric lamp or a wireless valve, you would no doubt reply, quite correctly, that there was a vacuum. But what is a vacuum? The dictionary says that it is a space entirely devoid of matter. In other words every particle of air that was originally inside the bulb has been removed and it now contains nothing whatever. But does it? Well, not quite. Wonderful though the achievements of science are, it has not yet succeeded—and in all probability it never will succeed—in producing the complete emptiness that is the perfect vacuum. Before the process of pumping out starts the bulb is full of air in its normal condition and a cubic millimetre of such air (a cubic millimetre is about the size of a pin's head) contains 40,000,000,000,000,000 molecules of gas—and a molecule, remember, consists of several atoms, each of which may contain many protons and electrons. The pumping out process produces what we are pleased to call a vacuum by removing all but one ten-millionth of the original air. But if you divide 40,000,000,000,000,000 by 10,000,000 the answer is four thousand million; and that is the number of molecules of gas left in each cubic millimetre of the so-called empty space, of vacuum! The human population of the world is about two thousand millions, so that each pin's head of volume in a bulb where what we proudly call a vacuum exists still contains enough molecules of gas to provide two apiece for every man, woman and child in all the countries of the world. A molecule is far bigger than an atom and enormously larger than an electron. You will see, then, that an electron is a very tiny thing indeed. It is many millions of times too small to be visible under the most powerful of microscopes. And it is so light that it can be made to start, to travel at tremendous speed, to stop, to reverse its direction and to start again thousands of times in a single second without any appreciable time-lag. Thus the electron furnishes the means whereby the kind of stopwatch that we need for radar can be contrived. That stopwatch is called the cathode-ray tube.

CHAPTER VII

The Radar Stopwatch

THE cathode-ray tube is one of the most interesting and ingenious of all the inventions that Man has made. Its applications to-day are innumerable and one or two of them are familiar to many people. A simple form of this tube, for instance, forms the "magic eye" tuning indicator with which some wireless receiving sets are provided. The cathode-ray tube is also the heart of the television receiver; the viewing screen upon which the images appear is nothing more or less than the end of a large cathode-ray tube. Like many ingenious and useful appliances the cathode-ray tube is really a very simple device and if you have grasped what Chapter VI told you about the electron you will have no difficulty in understanding the explanation which follows of the way in which it works. The main points to bear in mind are that an electron is a minute charge of negative electricity and that like charges repel like whilst unlike charges attract one another.

The simplest way of understanding what the cathode-ray tube does and how it does it is to follow out the various stages of its development. In Fig. VII. 1 is seen an ordinary electric lamp with a glowing filament. When the filament of such a lamp is heated to incandescence a tremendous commotion occurs amongst the atoms of which it is made up and something rather strange takes place: electrons actually leap from the filament, travel for a little time outside it and then return to it. The result of this is that at any instant the hot filament is surrounded as indicated in Fig. VII. 1, by a swarm of electrons in rapid motion. Now suppose that a metal plate is sealed into the bulb, as shown in Fig. VII. 2, and given a positive charge. What will happen to the electrons thrown out from the filament? The positive charge on the plate exerts an enormous attraction upon them—positive charges attract negative charges—and many of them are drawn through the vacuum of the bulb to the plate. This, incidentally, is the basic principles of the wireless valve as well as of the cathode-ray tube.

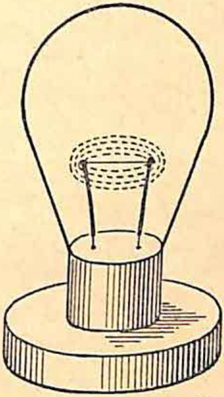
FIG. VII. 1.—A hot filament is surrounded by a swarm of electrons.

The plate is called the ANODE and the starting point of the electrons (the filament) the CATHODE. The process of harnessing the electron and making it do what we wish is carried a step further in Fig. VII. 3. Here a small hole has been pierced in the anode and a few of the fast-travelling electrons pass through it to continue their journey until they are brought up by hitting the end of the tube. We now have something like a beam or ray of electrons passing right across the bulb; it comes from the cathode, so we may call it a CATHODE-RAY. But it is a diffuse beam,

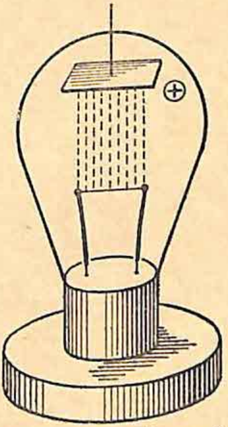

FIG. VII. 2.—If a positively charged plate is placed in the evacuated bulb, electrons are attracted by it and stream across from the filament.

for electrons are scattered all over the end of the tube, and the apparatus is distinctly inefficient, since only a small proportion of the electrons reaching the anode passes through the hole. Some means must be found of making the stream denser by forcing a much larger part of the electrons to take the desired path.

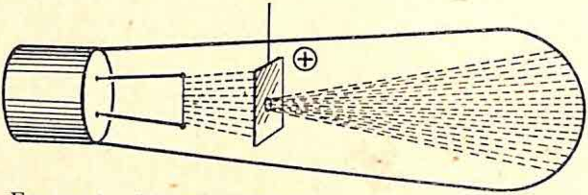

FIG. VII. 3.—When a small hole is made in the plate some of the electrons pass through it and reach the glass at the end of the bulb.

A step towards this is shown in Fig. VII. 4. Round the cathode is placed a metal cylinder, closed at its outer end save for a small aperture. This cylinder is called the GRID. It is given a negative charge and arrangements are made so that this charge can be increased or decreased by turning a control knob one way or the other. Repelled by the negative charge on the walls of the grid, the electrons

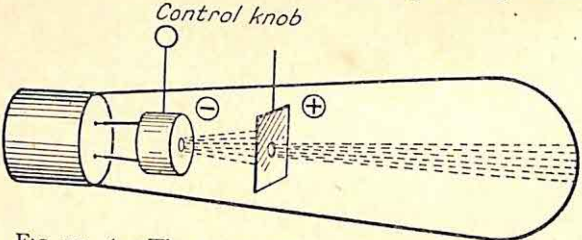

FIG. VII. 4.—The next step is to place a "grid" round the filament. This is a metal cylinder, closed at one end except for a small aperture. By means of a control knob the negative charge on the grid can be increased or decreased.

are, so to speak, concentrated in the middle part of the cylinder and then forced through the hole under the attraction of the positive charge on the anode. One result is that they are less scattered and a larger proportion passes through the aperture in the anode.

If the control knob is turned until the negative charge on the grid is great enough, the attraction of the anode is altogether cancelled out; no electrons pass through the hole in the grid and the electron stream is completely cut off. Reducing the negative charge on the grid steadily by means of the control knob allows the anode to exercise more and more influence; the stream of electrons becomes denser and denser. Thus the grid with its control knob provides a means of regulating the flow of electrons from the cathode to and through the anode.

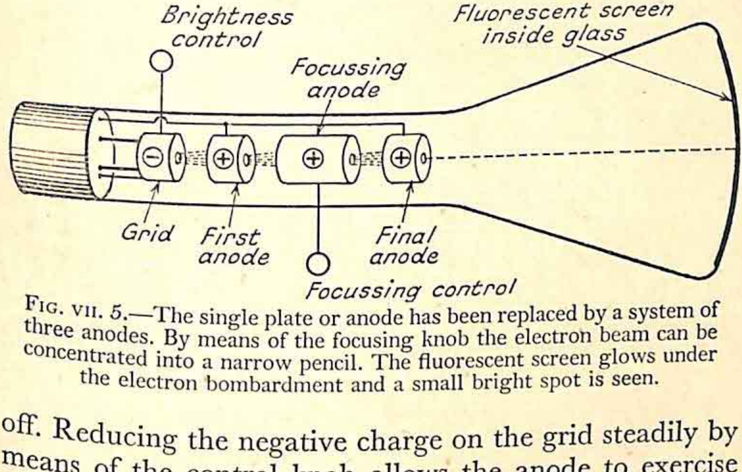

FIG. VII. 5.—The single plate or anode has been replaced by a system of three anodes. By means of the focusing knob the electron beam can be concentrated into a narrow pencil. The fluorescent screen glows under the electron bombardment and a small bright spot is seen.

The beam of electrons reaching the far end of the bulb is still wide and diffused. To enable it to do useful work some means must be found of focusing it to a point, just as a beam of sunlight is focused by a burning glass. Fig. VII. 5 shows the way in which this is done. Instead of a single flat anode, three of tubular shape are used as a combination. To explain just how this triple anode system focuses the electron beam would mean going into technicalities which would be out of place in a book such as this. All that need be said is that the three anodes do form what is to all intents and purposes a lens and that the beam can be made wider or narrower or focused to a small spot on the end of the tube by varying the positive charge on the middle or FOCUSING ANODE by means of the control knob. The intensity or pressure of an electric charge is known as its POTENTIAL and we shall use that term from now onwards. Potentials are measured in VOLTS, the units of electric pressure.

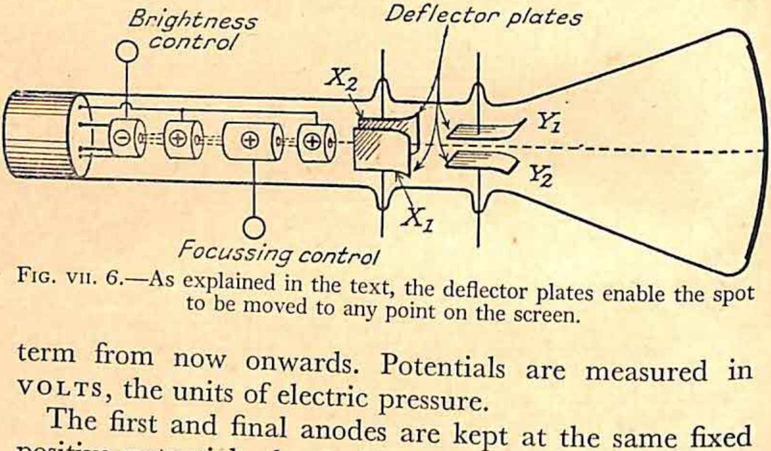

FIG. VII. 6.—As explained in the text, the deflector plates enable the spot to be moved to any point on the screen.

The first and final anodes are kept at the same fixed positive potential; the positive potential of the focusing anode can be varied by means of the FOCUS CONTROL knob. The electron beam is invisible, but it can be made to produce something which the eye can see. To do this the inside of the glass at the far end of the tube is coated with a material which glows when bombarded by fast-moving electrons. This glowing is called FLUORESCING, and the coated end of the tube is known as the FLUORESCENT SCREEN.

Let us take stock of what we have done so far. We have produced a beam of electrons which strikes the screen at the far end of the tube and makes it glow. We can focus the beam to a point so that one small, glowing spot is visible on the screen. And we can control the brightness of this spot. The denser the stream of electrons striking the screen the brighter will the spot be. That density is controllable by means of the knob which varies the negative potential on the grid and for that reason this knob is known as the BRIGHTNESS CONTROL. Our achievements at this point, then, amount to this: we have produced a stationary spot of light in the middle of the screen and we can vary at will both the brightness and the sharpness of the focus. The next thing is to devise some means of making the spot move to any desired part of the screen.

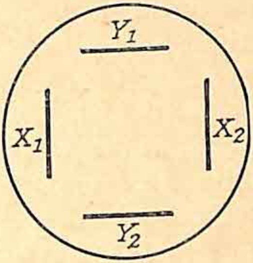

FIG. VII. 7.—The deflector plates as they would be seen from the wide end of the tube if the screen were transparent.

The electrons have proved delightfully amenable to the harnessing process so far as it has gone; they show themselves to be equally willing when it is taken a step further. Fig. VII. 6 shows a complete cathode-ray tube in simplified form. It differs from Fig. VII. 5 by the addition of two pairs, one vertical and one horizontal, of DEFLECTOR PLATES. The vertical pair are known as the *X*-plates and the horizontal pair as the *Y*-plates. The electron beam passes first between the *X*-plates and then between the *Y*-plates. Fig. VII. 7 shows the two pairs of plates as they would appear from the wide end of the tube if they could be seen through the fluorescent screen.

Now suppose that a positive potential is applied to the X_1 plate. The beam consists of negative electrons which are attracted by the positively charged plate; it is therefore pulled aside and the spot moves over towards the left of the screen. The same result could be obtained by making *X*2 negative. The electrons would then be repelled and the beam pushed away from *X*2. Similarly the spot can be made to move to the right by making *X*2 positive or *X*1 negative. The distance which it moves from its normal position in the centre of the screen depends on the magnitude of the potentials applied. The greater the positive potential of *X*1 (or the negative potential of *X*2) the further to the left will the spot move; the amount of its movement to the right is governed in the same way by the positive potential applied to *X*2 or the negative potential applied to *X*1.

Just as the *X*-plates control the horizontal movements of the spot, so do the *Y*-plates control its vertical movements. It can be drawn up by making *Y*1 positive or pushed up by making *Y*2 negative; if *Y*2 is made positive or *Y*1 negative it moves downwards.

Where there is no charge on any of the plates the spot remains stationary at the centre of the screen, for the beam is not being pulled or pushed in any direction. The same thing happens if all the plates have an equal positive potential: it is then attracted equally by all and does not move, for the pull of *X*1 just cancels out the pull of *X*2 and the pull of *Y*1 and *Y*2. An equal negative potential on all plates would also keep the spot motionless in the centre of the screen, for the beam would be repelled equally by all the plates. But by applying suitable potentials to various plates we can cause the spot either to take up any desired position on the screen, or to move about it as we wish.

It is this single spot, moving at enormous speed and being made to vary its brightness as required, which "paints" the images seen on the screen of a television receiver. The spot can indeed be made to travel at immense speeds and to stop, change its direction and restart with almost incredible rapidity. When a 10 by 8 inch image is on the viewing screen of a television receiver the spot travels over 202,500 inches a second, or rather more than 11,500 miles an hour (an amazing thought that, if you watch a television programme for just over two hours, the spot producing the images has travelled a distance equal to once round the Earth in that time!) and reverses its direction over 40,000 times a second.

In Chapter v we saw that no kind of mechanical device could be used for timing the wireless echoes used in radar. All such devices must contain moving parts made of metal or some other substance which suffers from the handicaps imposed by momentum and inertia. Such things, if we make them move at great speed, cannot be stopped and re-started readily, for their momentum resists any attempt to stop them when they are in motion and inertia makes them reluctant to start moving again after they have been brought to rest. It is no bad achievement mechanically to make a motor car or aeroplane engine which works at 3,000 revolutions a minute. Suppose that the pistons travel five inches downward, stop, reverse and then move five inches upward at each revolution. In that case the pistons stop and re-start in the opposite direction one hundred times a second. What is the average speed of the pistons? They travel five inches down and the same distance up fifty times a second; hence in one second their journey is 500 inches, which works out at a little over 28 miles an hour. Even if we can double or treble the number of revolutions a minute we have no performance that can compare with that of the spot of the cathode-ray tube.

By harnessing the electron we are able to obtain vastly greater speeds and to increase very greatly the number of times a second that stopping and re-starting can be accomplished—and all this without the wear and tear or the generation of unwanted heat that would have to be got rid of were any sort of mechanical means employed to provide the very rapidly repeated movements that are required for measuring minute amounts of time.

Think what would happen if even the smallest and lightest conceivable moving part of metal were suddenly stopped when travelling at some 10,000 miles an hour—about five times as fast as a rifle bullet. Just as a bullet is smashed when it is brought up short by a stout sheet of armour, so the part in question would be destroyed; there could be no question of its reversing its direction or repeating the movement. The beam of electrons, however, which produces the spot of light by its impact on the fluorescent screen of the cathode-ray tube does such things without any untoward incidents.

The spot, let us take it, is stationary at the centre of the screen there being at the moment no charge either positive or negative on any of the plates. What will occur if we apply a rapidly increasing positive potential to the *X*2 plate? The higher the potential the further will the spot be pulled from its central position towards the right as we face the screen. Now let the potential on *X*2 be suddenly reduced to zero. By "suddenly" I do not mean that the removal of the positive attracting potential occurs in no time at all: any event must occupy some time, however minute that time may be. Actually the potential on *X*2 may be lowered from a thousand volts or more to zero in a millionth of a second or less. A millionth of a second may seem to be so short a space of time that it is hardly worth thinking about; millionths of a second, though, are important in radar: in fact, to obtain accurate ranges we must be able to measure not just millionths, but fractions of a millionth part of a second.

But, leaving aside such considerations for the moment, imagine that the pull of the *X*2 plate on the spot is suddenly relaxed. The spot is now under no deflecting influence at all and it flashes back to its original central position. There is no shock, no generation of heat when its rapid movement to the right is stopped by the cessation of the pull by the *X*2 plate; it flies back to the middle of the screen and is at once ready to start a fresh rapid journey to the right if an increasing positive potential is again applied to the *X*2 plate.

There is no great difficulty electrically about applying a steadily increasing positive potential to X2, or about making the increase continue for a definite time (which may be very small indeed) or again about ensuring that at the end of that time the potential drops suddenly (remember what was said in the last paragraph but one about that word "suddenly") to zero. The result of all this is that we can make the spot travel for a definite time to the right and then fly back to the centre of the screen. As the amount of its movement to the right depends upon the magnitude of the attracting potential, we can, if we wish, so arrange matters that the outward movement of the spot towards the right is at a uniform speed. It is also possible to draw the spot over to the right and then allow it to flash back to the centre at regular intervals and, within reason, we can do this as many times a second as we find necessary.

The electrical appliance with the help of which the positive potential on *X*2 is made to increase is called a CONDENSER. The strictly correct name is capacitor, but as condenser is the more familiar term, we will use it.

With the aid of the condenser the potential can be made to rise from nothing to a required maximum amount in a definite time. All motorists have frequent practical demonstrations of its performance of a task similar to that mentioned. Just before you arrive at an automatic traffic light you pass over a bumper bar in the roadway. The depression of this bar by the weight of the car brings a condenser into action. It at once begins to charge—that is, to build up a higher and higher potential—and when the potential has risen sufficiently switches are actuated which operate the lights, giving you the right of way and closing the cross-road to traffic. As the condenser can be arranged to charge in any required time, you will receive the green signal after a number of seconds previously decided upon by the authorities who were responsible for installing the traffic lights. The actuating potential is removed after your car has passed by the discharge of the condenser and the lights are switched to their former colours.

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CHAPTER VIII

Very Big—and Very Small

IT has been mentioned that in order to obtain accurate ranges with radar gear we must be able to measure the time of the out and home journey of the wireless waves reflected from the target to a fraction of a millionth of a second. That expression "millionth" of a second, by the way, is rather cumbersome and as we can say the same thing in one word instead of in four by calling it a MICROSECOND we may as well do so from now onwards. Besides millionths, we have also gone to the other end of the scale by speaking of millions—light waves and wireless waves travel at a speed of three hundred million metres a second; millions of atoms lose or gain an electron every second when an electric battery is in use and so on. Before we go any further it will be useful to try to find some means of realising what a vast number a million is and how tiny a fraction is a millionth.

It is difficult for human beings to form a mental picture of any mass of men or things much exceeding a thousand in number—and one million is a thousand times a thousand. It is easy enough to grasp what an assembly of a thousand men looks like, for you have only to think of a regiment of soldiers marching past a point or drawn up on a parade ground; but you cannot picture a thousand regiments presenting arms simultaneously on a thousand parade grounds. Novelists and film scenario writers are wont to depict the prospector who has made a lucky strike fighting his adventurous way back to civilisation with his million-pound fortune in gold dust or nuggets borne on his own bowed back or on that of his faithful "burro." Either back would indeed be bowed, for even at £7 an ounce a million pounds' worth of gold weighs almost four and a half tons—and many of these books and film scripts were written in days when the value of gold was less than half what it is now!

Could you say offhand how far ahead is a million seconds from the moment when you read these words? What was happening a million minutes, or hours or days ago? Before reading any further make your own rough estimates of the answers to these questions.

Well, a million seconds come to rather more than eleven and a half days and a million minutes to the best part of two years. A million hours ago Queen Victoria's long reign had not begun and a million days take us back to the time of the prophets Elijah and Elisha.

Travelling at 300,000,000 metres a second, wireless waves could make between seven and eight journeys round the earth in the time that a clock's pendulum needs to complete its swing. If ever you have listened to the B.B.C.'s oversea transmission on 13 metres you may have noticed a curious effect: a speaker appears to be afflicted with a rapid stammer, for a kind of ghost of each syllable is heard just after it has been uttered. The doubling of sounds is due to the fact that your aerial is receiving the waves first of all direct and then a second time after they have journeyed right round the world. On some occasions the sounds are triplicated or even quadruplicated as the waves return after successive round-the-world trips.

It is perhaps even more difficult to form an idea of a space of time so short as a millionth of a second. Speeding along at 60 miles an hour, an express train covers in one microsecond (Fig. VIII. 1) a distance about equal to the thickness of a single sheet of fine India paper. The briefness of the microsecond can perhaps be realised when it is mentioned that no fewer than 947 of them elapse whilst a 60 miles-an-hour express moves forward a single inch on its way! Yet the cathode-ray tube, used as a stopwatch in the way to be described in the next chapter enables such tiny time intervals to be measured easily and with exactness.

Why is it necessary to measure so minutely and so exactly? Accurate ranges are obviously required for gunnery purposes if hits are to be scored. They are needed, too, for many of the wonderful radar aids to navigation on the sea and in the air. One type of radar, for example, enables the pilot of a ship steaming in dense fog to locate the buoys marking a narrow channel as well as other craft that may be on or near his course. Such apparatus would be of little use if it gave only an approximate idea of distances: the ranges which it records must be accurate to a few feet.

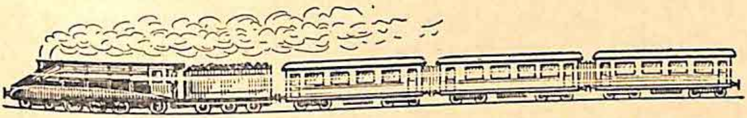


FIG. VIII. 1.—An express train travelling at 60 miles an hour advances just over a thousandth of an inch in one microsecond. Whilst it is covering a single inch of track, 947 microseconds elapse.

From the radar transmitter wireless waves travel out to the target, are reflected from it and return as echoes. We saw in Chapter IV that the speed of wireless waves is roughly 186,000 miles a second. The exact figure is 327,720,000 yards a second. If the target is one mile away the waves make a double journey of two miles:

transmitter—target—receiver. The time required for this is 10.7 microseconds. If the range is two miles, the time is 21.4 microseconds; if 20 miles, 214 microseconds. In other words, every mile of range means a delay of 10.7 microseconds between the departure of the waves from the radar transmitter and their return to the receiver. Radar apparatus such as is used purely for the long-distance location of targets may not need to make minute measurements with the most extreme accuracy. It can tell us that there is a target about 75 miles away so long as it is capable of indicating that the time for the out-and-return journey of the waves is somewhere in the neighbourhood of 800 microseconds—an error of a few millionths of a second either way would be of no great importance.

Matters, though, are very different when we come to the exact ranges required for navigation aids of the highest precision and by gun and torpedo detachments when they are engaging a target. They need not the approximate range in miles, but the range in yards with the least possible error. The time for the double journey of waves representing 1,000 yards of range is 6.1 microseconds: 6.1 microseconds elapse between the departure of the wireless waves and the return of the echo for every 1,000 yards of range. But to be able to locate the target exactly or to hit it with shells or torpedoes we must know the range much more accurately than to the nearest 1,000 yards. If each 1,000 yards of range means a time of 6.1 microseconds, then each 100 yards will mean one-tenth of that; 0.61 microseconds or sixty-one hundred-millionths of a second. And even 100 yards is a much greater error in range than could be tolerated; by radar methods ranges can be measured with a maximum error of less than 25 yards. You will see that the kind of radar equipment used for supplying accurate ranges for navigation purposes or when the target is close enough to be engaged by guns, must be able to measure fractions of a microsecond if the information that it gives is to be of real value. And now let us see how the harnessing of the electron in the cathode-ray tube enables these wonderful things to be done, not by experts, working in the peace and quiet of a laboratory, but by ordinary men and women, operating radar apparatus in ships or aeroplanes or the control towers of aerodromes—or even in the din and turmoil of a battle.

CHAPTER IX

Measuring Millionths of a Second

THE face of a watch or clock is so familiar a thing that probably you have never given it a thought since you acquired the knack in your childhood's days of telling the time from it by a glance at the position of the hands. Like so many other familiar things, it may hardly seem worth thinking about. And, anyhow, what *is* there to think about in a couple of pointers moving over a scale graduated in hours and minutes and showing what time it is? Well, there is quite a bit; and if we spend a moment or two in considering what takes place on the face of a clock, it will be of considerable assistance in enabling us to see how electrons are used in the cathode-ray tube to time the microseconds of radar.

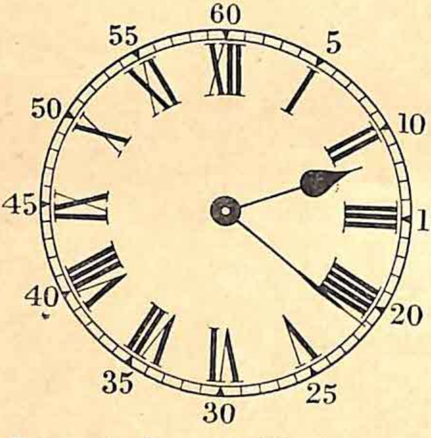


FIG. IX. 1.—As explained in the text, the clock face is two time scales in one.

Could you, by the way, draw a clock dial without looking at a clock or watch, or at Fig. IX. 1? Try and see. It is more than likely that you will make several mistakes—

which goes to show how small is the impression on our minds made by what we are pleased to call familiar things!

Have you made your attempt? Did you put IIII or IV? VI or IΛ? VIII or IIIΛ? I confess freely that I did not get Fig. IX. 1 right the first time that I drew it! It does not count as a mistake if you have omitted the figures 5, 10, 15, 20 and so on for the minutes, since these appear on few clocks or watches made in recent years.

The clock face actually contains two time-scales in one, and each scale has its own indicator in the hour hand and the minute hand. The hour scale is traversed completely once in twelve hours by the hour hand; it has twelve equally spaced marks, usually numbered by Roman figures. The minute scale, over which the minute hand passes, has 60 equally spaced divisions, each corresponding to one minute. We know the clock face so well nowadays that there is no need to number the minutes. We can tell by a glance at the minute hand whether it is 5 or 15 or 25 minutes past the hour. In the old days, when watches were rarities and there were comparatively few clocks, people had some difficulty in telling the time and numbering the minute divisions was necessary. Now everyone knows the clock-face so well that in some ultra-modern timepieces there are no numbers at all, even the hours being indicated by black marks all of the same size and shape.

If you consider the hour hand, you will realise that the time is indicated by the distance which it has moved from a vertical position. It points straight upwards at twelve o'clock; when it has performed a quarter of its journey round the circular dial the time is three o'clock; six o'clock at the half-way mark; nine o'clock when three-quarters of a complete revolution has been made. When it has completed a revolution on coming to twelve o'clock, it repeats the performance. It does not need to stop and restart on reaching the end of the scale, since the dial is circular and the motion can therefore be continuous: twelve o'clock and "nought o'clock" are the same thing.

It would be easy to devise a straight-line scale, as illustrated in Fig. IX. 2. In this case the indicator would travel from left to right and, on reaching the twelve o'clock position, would fly back to zero. Actually no fly-back would be needed if several indicators were used, one appearing at the left edge of the scale as another disappeared at the right edge. The mechanically minded may amuse themselves by thinking out ways of doing this.

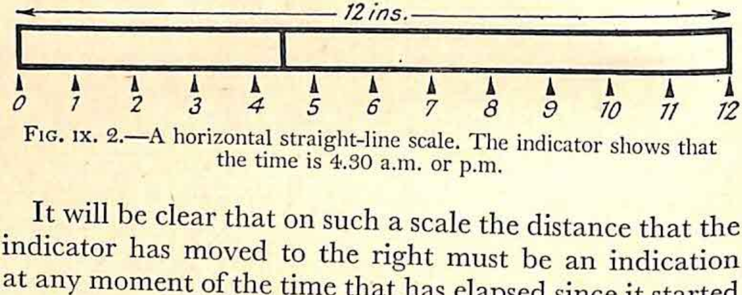


FIG. IX. 2.—A horizontal straight-line scale. The indicator shows that the time is 4.30 a.m. or p.m.

It will be clear that on such a scale the distance that the indicator has moved to the right must be an indication at any moment of the time that has elapsed since it started its journey from the left end. Make the scale twelve inches long, and you can measure time with a footrule, even if no marks or figures appear on the scale. If the pointer has moved $7\frac{5}{12}$ inches towards the right, the time must be $7\frac{5}{12}$ hours, or twenty-five minutes past seven o'clock.

Any device in which the distance travelled by an indicator corresponds to the time which has elapsed since it started on its journey is called a TIME BASE. The clock-face is a simple and familiar form of time base—two time bases in one, since there is an hour time base and a minute time base on the same scale. When the cathode-ray tube is used as a stopwatch we may use a horizontal time base of the kind seen in Fig. IX. 2, with the difference that the indicator is not a hand or a pointer, but the spot of light due to the beam of electrons impinging on the fluorescent screen.

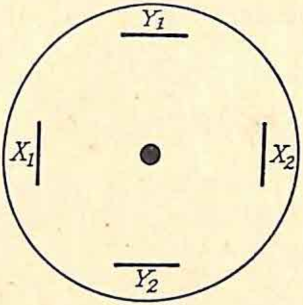


FIG. IX. 3.—No potential applied to any plate. The electron beam is not deflected in any direction and the spot remains stationary at the centre of the screen.

We saw in Chapter VII that by applying an increasing positive potential to the $X2$ plate the spot can be made to travel farther and farther to the right and that if this potential is suddenly removed, the spot then flies back to the centre of the tube. As no mechanical parts are involved and as the electron beam is to all intents and purposes unhandicapped by inertia and momentum, we can make the spot's journey across the tube very rapid and we can cause it to be repeated at exceedingly short intervals of time.

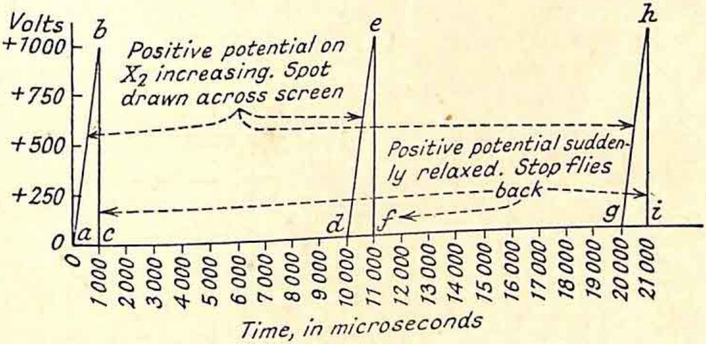


FIG. IX. 4.—To make the spot travel across the screen 100 times a second and to take 1,000 microseconds for its journey a rising positive potential is applied to X_2 for 1,000 microseconds and then suddenly removed. This is repeated 100 times a second.

Fig. IX. 3 shows the position of the spot when all plates are at zero potential: the electron beam now undergoes no deflection and the spot rests at the centre of the screen. Let us suppose that we require to make the spot travel for 1,000 microseconds to the right, flash back to its starting point, and repeat its travels 100 times a second. The way in which this may be done is indicated in Fig. IX, 4. To the $X2$ plate is applied a positive potential which rises in 1,000 microseconds, as shown by the lines *a-b*, *d-e* and *g-h* to whatever maximum value is selected. As the potential rises the pull of the $X2$ plate increases accordingly and the spot is drawn (Fig. IX. 5) more and more to the right. At any instant the position of the spot on the screen is exactly determined by the value to which the potential has risen. When the maximum is reached the spot is at the limit of its journey to the right. If the positive potential is now suddenly removed from $X2$ (Fig. IX. 6) the pull ceases and the spot flies back to its rest position at the centre of the screen, where it

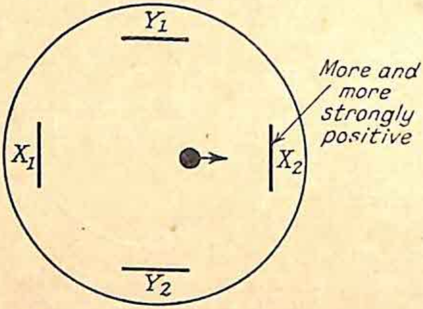


FIG. IX. 5.—A rising positive potential is applied to X_2. The spot moves farther and farther to the right.

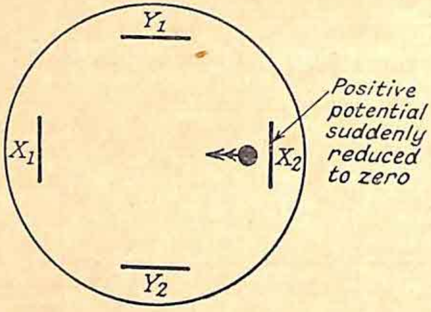


FIG. IX. 6.—The positive potential on X_2 is suddenly reduced to zero. The spot flies back to the centre.

remains until the positive potential on X_2 again starts to build up.

In Fig. IX. 4 the lines *b-c*, *e-f*, *h-i* indicate the sudden fall in potential from maximum (here 1,000 volts) to zero. By "sudden" I do not mean to suggest that this fall occupies no time at all: it can take place very rapidly (in a microsecond or so) but a definite time, however short, is required for the process. Now consider Fig. IX. 4 for a moment in connection with Figs. IX. 3, IX. 5 and IX. 6. At *a* in Fig. IX. 4 the X_2 plate is at zero potential and the spot is in its rest position. As the potential rises for 1,000 microseconds towards *b* the spot moves to the right. When *b* is reached the potential is removed, falling very rapidly to *c*, where it is zero. The spot flies in perhaps one microsecond to the centre of the screen where it remains for $9{,}000 - 1 = 8{,}999$ microseconds until the next rise begins at *d*. And so the process is repeated once every 10,000 microseconds, or 100 times a second. It can be made to repeat itself much more rapidly if necessary.

In making its movements the spot, incidentally, does some pretty fast travelling. If its journey to the right in 1,000 microseconds is six inches, its speed is 340 miles an hour; but the return journey is done in one microsecond, or one-thousandth of the time, and its speed then reaches the rather staggering figure of some 340,000 m.p.h.

Even on its comparatively slow outward journey the spot is travelling far too fast for the eye to see it as a spot. What the eye sees on the screen is a glowing line (Fig. IX. 7), which is

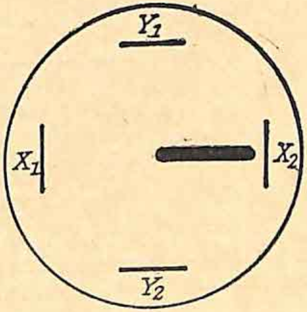


FIG. IX. 7.—So rapid are the movements of the spot that the eye sees a glowing line on the screen.

time that has passed since it began its journey from the cross-wire?

We have still a pair of deflector plates to make use of, for so far we have done nothing with Y_1 or Y_2. The effect of applying either a positive potential to Y_1 or a negative potential to Y_2 is to make the spot move upwards on the screen. What we can do is to make the echo on its arrival from the target cause a negative potential to be applied for an instant to Y_2.

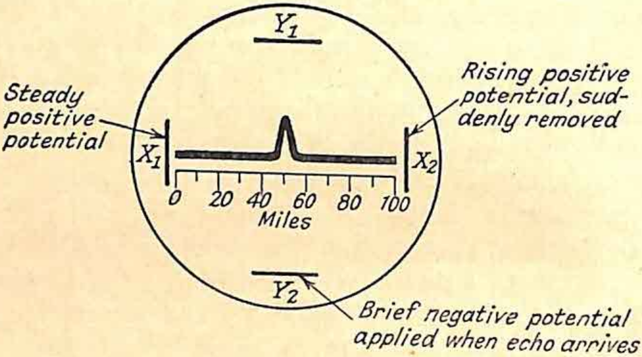

Y_1
Steady positive potential
Rising positive potential, suddenly removed
X_1
X_2
0
20
40
60
80
100
Miles
Y_2
Brief negative potential applied when echo arrives

FIG. IX. 11.—The echo on arrival at the receiver is used to cause a brief negative potential to be applied to Y_2. This repels the electron beam and pushes the spot upwards, producing a "break" on the trace. In the figure the position of the break shows that the range to the target is about 45 miles.

The spot, having started from the cross-wire at the left, is moving smoothly on its way across the screen. Suddenly Y_2 receives a negative potential. At that instant the spot is pushed upward, falling to its normal level and continuing on its way as soon as the negative potential is removed. This upward and downward movement causes the trace to develop a kink, shaped like an inverted V, which is known as the BREAK or "Blip." As shown in Fig. IX. 11 the position of the break on the scale indicates the time that has elapsed and therefore the range to the target. Here the break begins half-way between the 40-mile and 10 50-mile marks and the measured range is 45 miles. In the next chapter we shall see how the spot is made to start on its journey at the right moment and how the break is caused by the echo.

CHAPTER X

Finding Accurate Ranges

IF you are measuring a range by the sound-echo method described in an earlier chapter, you shout "Hi!" or make some such short sharp sound, start the watch as you

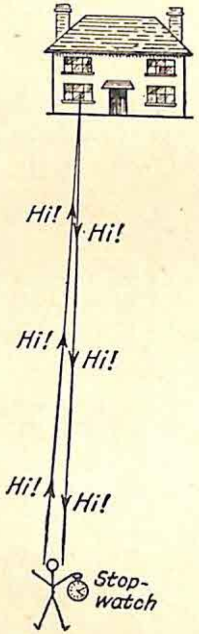


FIG. X. 1.—When measuring range by sound echo it would be useless to send out either a long-drawn-out note or a very rapid succession of "Hi's!", for you would not be able to tell which part of the note or which of the "Hi's!" you were timing.

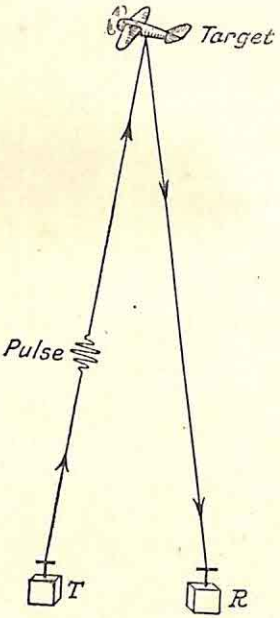


FIG. X. 2.—With Radiolocation gear a brief "whiff" of wireless waves, or pulse, is sent out. This is the wireless counterpart of a shouted "Hi!" Time must be allowed for each pulse to complete its double journey before the next is sent out.

shout and stop it when the echo reaches your ears. Having worked out the range, you can check it by repeating the process as soon as you are ready to do so. A glance at Fig. X. 1. shows that neither a sustained sound nor a too rapid succession of "Hi's!" would be of much use; you could not tell which part of the long-drawn-out note, or which of the "Hi's!" you were timing. It will be plain, then, that the following principles must be accepted for any kind of range measurement by echo. (1) The impulses used to excite the echo must be short and sharp; (2) a second impulse must not be sent until the first has returned and has been timed. Or, to put the second principle in another way, the intervals between echo-producing impulses must be such that there is plenty of time for one to return and to be timed, and for the timing apparatus to be re-set before the next is sent out.

When a short, crisp sound such as a shouted "Hi!" is made, the vocal cords pass suddenly from rest to violent activity and after an instant come as suddenly to rest again. The sound does not begin softly, rise gradually to its greatest loudness and die gradually away, for the sudden strong vibrations of the vocal cords immediately produce large sound-waves and they are still large when the vibration of the cords is brought to an abrupt end. The radar counterpart (Fig. X. 2) of the shouted "Hi!" is a brief train of large wireless waves with an abrupt start and an abrupt ending. It is known as a PULSE and it is produced by bringing the transmitter suddenly into full activity and suddenly closing it down. This is done automatically by ingenious methods and it may be made to happen a thousand times a second, or oftener if required.

When the range of a target is being measured by radar two things are done simultaneously. As the direct pulse leaves the transmitter (*T* in Fig. x. 3) another pulse is sent by the transmitter over the short distance to the receiver (*R* in Fig. x. 3). This is known as the SYNCHRONISING or LOCKING PULSE and Fig. x. 4 shows what it does.

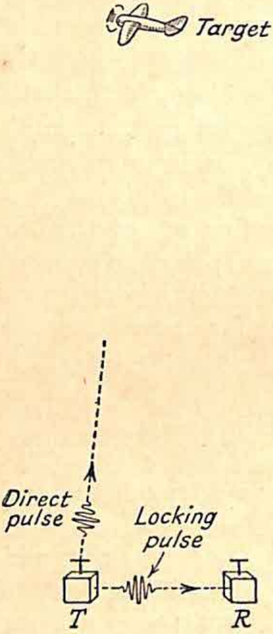


FIG. x. 3.—At the instant when the direct pulse leaves the transmitter for the target, another, the synchronising or locking pulse, is sent from the transmitter straight to the receiver.

On its arrival at the receiver, the locking pulse triggers off the time base unit, which at once starts to build up an increasing positive potential on the X_2 plate, causing the spot to leave its rest position at the hairline and to start moving towards the right of the screen. Thus the spot is started on its journey across the screen as the direct impulse starts on *its* journey towards the target. Actually there is a very slight delay in starting off the spot, for the locking pulse takes time—a very small amount of time, but, nevertheless, time—to travel from the transmitter to and through the receiver. But as this time can be measured, the slight delay can be and is allowed for in the range-measuring gear.

In Fig. x. 5 the echo pulse is represented as finishing its journey by reaching the aerial of the radar receiver. What then takes place is illustrated diagrammatically in Fig. x. 6. The rising positive potential applied to the X_2 plate by the time base unit is still pulling the spot to the right.

The echo pulse passes through the "Superhet" (short for superheterodyne receiver. Don't shy at the word. The great majority of ordinary domestic broadcast receivers are superhets) in which it receives enormous amplification.

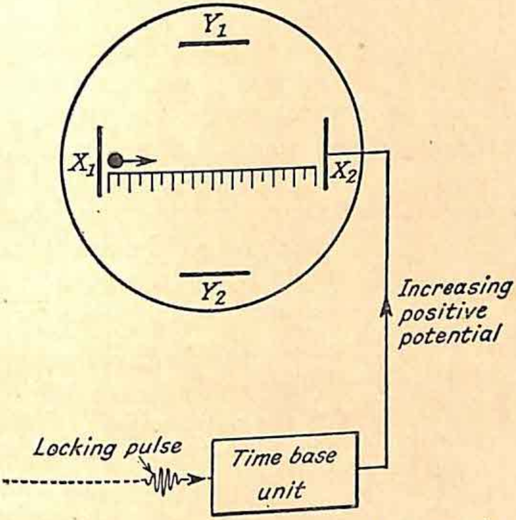


Fig. x. 4.—On reaching the time base unit the locking pulse triggers off a circuit which applies an increasing positive potential to X_2. The spot is thus made to start its travel over the screen when the direct pulse leaves the transmitter for the target.

It is next used to cause a negative potential of very brief duration to be applied to the Y_2 plate.

The return of the echo, therefore, gives a "whiff" of negative potential to Y_2, with the result that the moving spot is pushed upwards, as shown in Fig. x. 6, at whatever point it has reached in its horizontal journey across the tube. In the drawing the range indicated by the break so produced is 50 miles. The spot has thus been pushed upwards by the arrival of the echo pulse 50 × 10.7 or 535 microseconds after the departure of the direct and locking pulses from the transmitter. Fig. x. 7 shows in simplified diagrammatic form the whole process of range measurement.

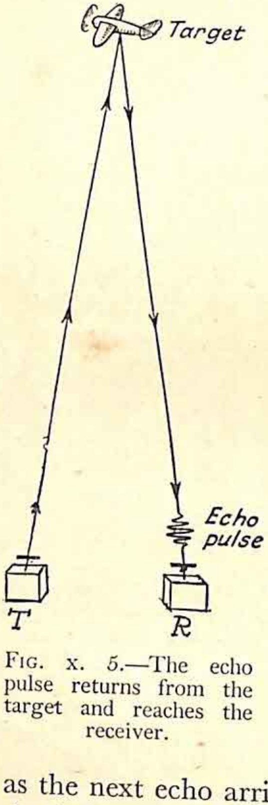


Fig. x. 5.—The echo pulse returns from the target and reaches the receiver.

After the break has occurred the spot continues its normal movement to the right under the pull of the X_2 plate. As soon as this pull is removed it flies back to the rest position and stays there until the arrival of the next locking pulse starts it on its travels once more. Its journeys may be repeated anything from 100 to 1,000 or more times a second. As we have seen already, a direct pulse and its accompanying locking pulse must not be sent out until enough time has elapsed for the echo of the previous one to have reached the receiver and to have been dealt with by it. There must then be time for the receiver to re-set itself so as to be able to perform its measuring operations again as soon as the next echo arrives. The longer the range for which the instrument is designed, the fewer the pulses sent out each second, for as the range is increased, so the time taken by the direct and echo pulses to travel to and from the target becomes greater.

Whatever the number of pulses sent out each second (or the RECURRENCE FREQUENCY, as it is called), the trace and the break on the screen of the cathode-ray tube present much the same appearance to the operator. If the target is a stationary one the time for the out-and-home journey is always the same; the break occurs at the same point on the scale, the many repetitions of the spot's movements serving to make trace and break clear and definite, just as one can blacken in a line in a drawing by going over it again and again with a pencil.

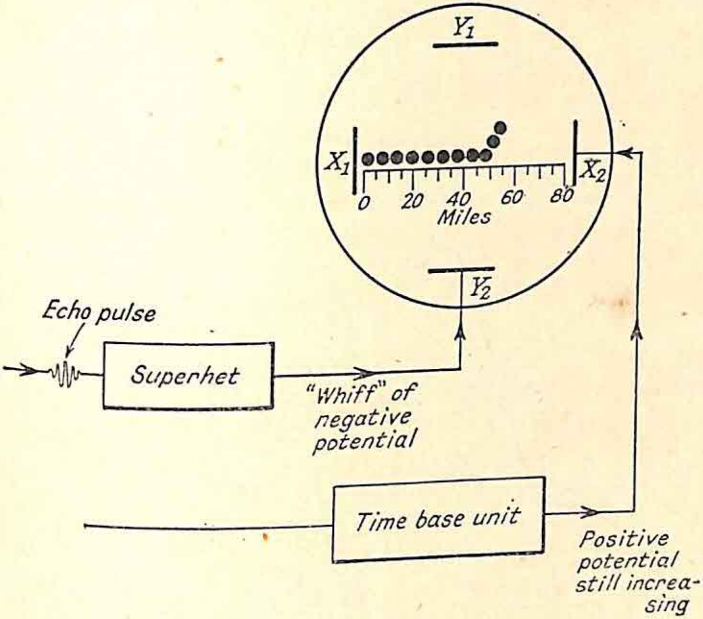


FIG. X. 6.—On its return the echo pulse is detected and enormously magnified by the superhet. It is then made to cause a brief negative potential to be applied to Y_2. The spot, still travelling to the right, is pushed up and the position of the break on the scale indicates the range.

If, however, the target is approaching, the time for the return of each echo is slightly shorter than that of its

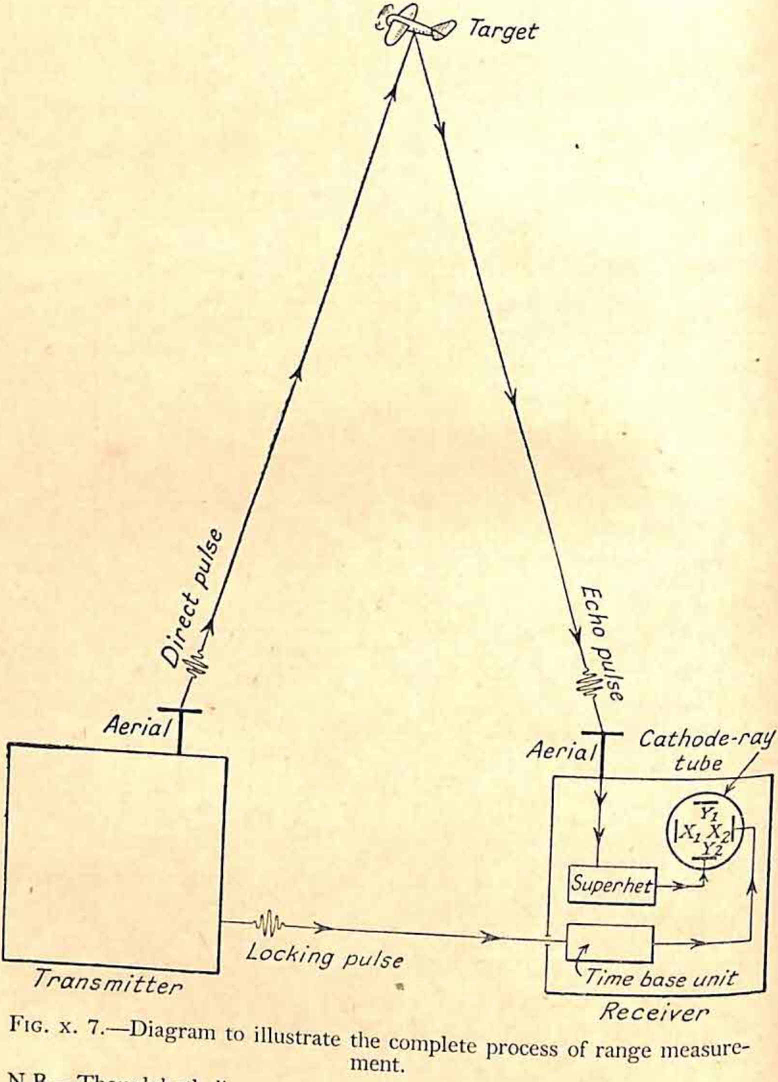


FIG. X. 7.—Diagram to illustrate the complete process of range measurement.

N.B.—Though both direct and echo pulses are shown, a direct pulse is not in practice sent out until the echo of the previous one has been received and timed.

predecessor. Hence each break occurs a tiny amount more to the left than the one before it. The eye cannot see the individual breaks, so rapidly do they follow one another, but it receives the impression that the break is moving to the left. Similarly, when a target is receding the break is seen to move to the right.

The method of measuring range by noting the position of the break with reference to a scale of miles or thousands of yards is obviously somewhat crude and would not allow very accurate measurements to be made. We shall see presently something of the ingenious combinations of electrical and mechanical devices which make it possible for a reasonably intelligent man or woman to be able to measure ranges accurately after a comparatively short period of training.

It has been mentioned that an important part of the electrical device which builds up an increasing positive potential on the X_2 plate is known as a CONDENSER. The condenser may be regarded as the electrical counterpart of a tank or reservoir. If electricity is made to flow into it, it eventually becomes full or "charged"; it is emptied or "discharged" by providing a means for allowing its electrical contents to flow out of it. Just as the time in which a given tank fills and empties can be regulated by increasing or decreasing the diameters of the inlet and outlet pipes, so the time needed to charge or discharge any condenser can be adjusted exactly by increasing or decreasing the resistance of the conductors through which electricity flows into or out of it. Electrical resistance is measured in units known as ohms. All the time that electricity is flowing into a condenser the pressure or potential is rising until a point is reached at which it is fully charged. When electricity flows out of a condenser the potential falls until the condenser is empty or discharged.

What may be termed the electrical size of a condenser is called its CAPACITANCE. This is a measure of the number of electrons that it will hold if a given electric pressure is applied to it for one second. The unit of capacitance is the FARAD; but this is far too large for ordinary purposes. A one-farad condenser would be about the size of a tramcar!

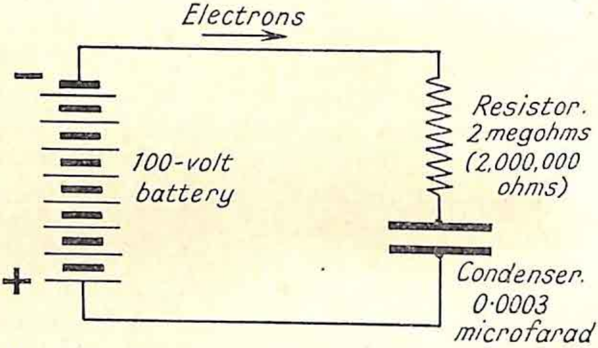

Electrons
−
+
100-volt battery
Resistor. 2 megohms (2,000,000 ohms)
Condenser. 0·0003 microfarad

FIG. X. 8.—If a condenser of 0.0003 microfarad is charged through a resistance of 2 megohms, the electrical pressure between its plates will always reach 63 per cent. of the applied voltage in 0.0003 × 2 second. This is known as the time constant of the circuit. In this example the pressure between the plates of the condenser rises to 63 per cent. of 100 volts, or 63 volts in 0.0006 second, or 600 microseconds.

The capacitance of the small condensers used on wireless, television and radar is measured in microfarads (millionths of a farad, symbol μF) or in micro-microfarads (billionths of a farad).

If an electric pressure is applied to a resistor and a condenser, arranged in series as in Fig. X. 8, the condenser will always charge to 63 per cent. of the applied voltage in a number of seconds equal to the capacitance in microfarads multiplied by the megohms (millions of ohms) of resistance. In the Fig. x. 8 example the applied pressure is 100 volts, the resistance 2 megohms and the capacitance 0.0003 μF. The condenser thus develops a pressure of 63 volts between its plates in 2 × 0.0003 = 0.0006 second, or six ten-thousandths of a second, or 600 microseconds.

It does not matter what the applied voltage is or what the capacitance of the condenser: whatever its capacitance, it will *always* charge to 63 per cent. of the applied voltage in the number of seconds (or microseconds) given by multiplying the capacitance in microfarads by the resistance in megohms.

This product is known as the TIME CONSTANT of a circuit containing a resistor and a capacitor in series. It is one of the most valuable properties of electrical circuits. It enables us (*a*) to make apparatus which will cause something to be done when a period of time, measured with absolute accuracy, has elapsed (the traffic lights on p. 68, for instance), or (*b*) to make other apparatus—radar, for example—in which time can be measured (again with absolute accuracy) to a fraction of a millionth of a second.

Note particularly that if the capacitance of the condenser is increased the time constant (and therefore the time needed for the condenser to charge to a given pressure) is also increased. We shall see presently how this principle may be employed for the precise measurement of range.

By selecting the proper condenser and the proper resistor the time taken for the build-up of the positive potential on the X_2 plate after the time base unit has been triggered off by the locking pulse may be made as long or as short as we require. Just how long we need the increase from zero to maximum to take will depend naturally on the maximum range that the apparatus is designed to measure. If we need our radar apparatus for early-warning purposes or for long-distance navigation aids to measure ranges of, say, 100 miles, the calculation is: every mile of range means 10.7 microseconds of time; therefore to be able to measure up to 100 miles, the spot must not take less than 10.7 × 100 = 1,070 microseconds to travel from its starting point to the opposite edge of the screen. We might, therefore, select a condenser and resistor to give a charging time of 1,500 microseconds, so as to allow a fair margin. On the other hand, if the apparatus is to be used for measuring ranges up to 40,000 yards we note that at 6.1 microseconds per thousand yards of range a time base for some 300 microseconds is called for and choose condenser and resistor accordingly.

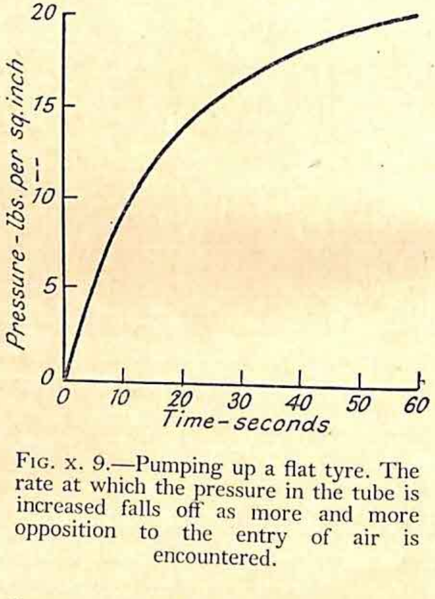


FIG. x. 9.—Pumping up a flat tyre. The rate at which the pressure in the tube is increased falls off as more and more opposition to the entry of air is encountered.

The charging of a condenser is not unlike the process of pumping up a flat bicycle tyre. To begin with the work is easy: the inner tube is empty and there is no pressure inside it to oppose the entry of the air driven in by the pump. But as an appreciable pressure builds up inside the tube there is greater opposition to the incoming of still more air. The work becomes harder and the rate at which the pressure in the tube is increased slows down. When the tyre is approaching full inflation the opposition is so great that the last few pounds of pressure take some little time to add. We can draw a curve like that of Fig. x. 9 to illustrate the process. The pressure rises rapidly in the first few seconds, but the rate of increase soon begins to tail off and in the last few seconds it is very slow indeed.

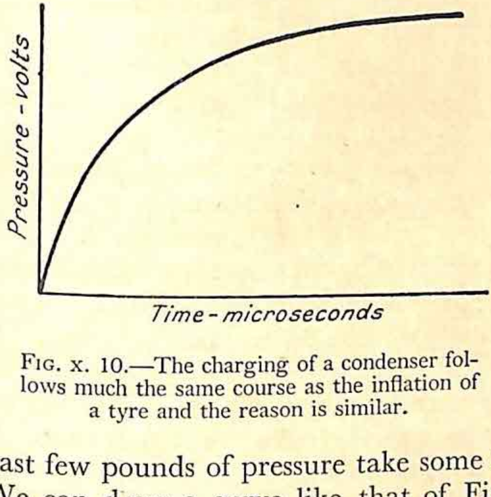
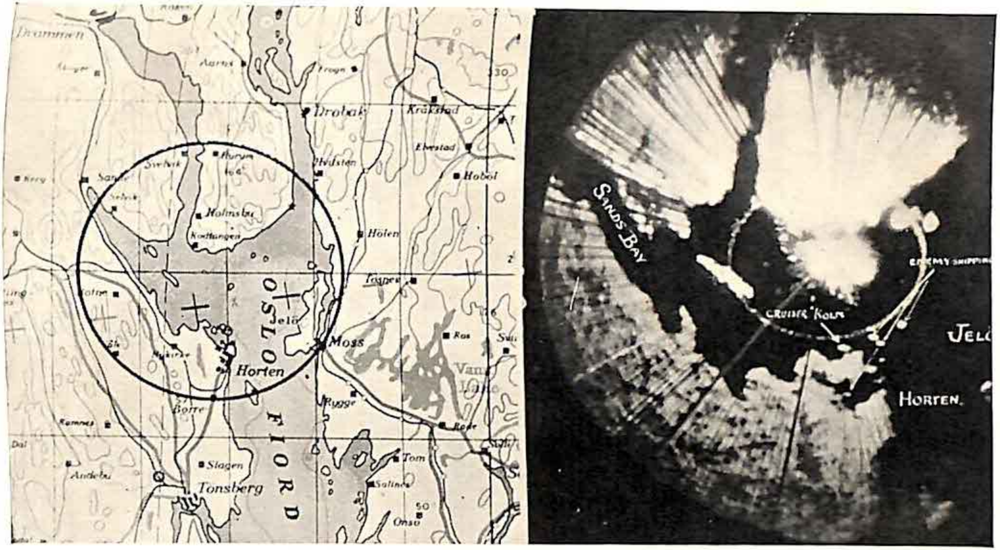


FIG. x. 10.—The charging of a condenser follows much the same course as the inflation of a tyre and the reason is similar.

In a similar way the pressure in a condenser increases quickly when it begins to charge, for there is to start with little or no internal pressure to oppose the entry of current. But as the internal pressure grows, more and more opposition is offered and the increase is much slower when the condenser is approaching its fully charged state. It will be seen that the curve shown in Fig. x. 10, which illustrates the charging of a condenser, is of the same general shape as that of Fig. x. 9. It follows that if the charging of a condenser is used to provide the increasing positive potential on the X_2 plate which draws the spot across the screen the increase of potential will not take place at a uniform rate. The potential on X_2 will rise rapidly at first, but there will be a tailing off in its rate of increase. Hence the speed at which the spot travels will also not be uniform: it will be moving less rapidly towards the end than at the beginning of its travel. That, however, does not matter in the least so long as it completes its journey (as it does) in the required time and so long as the rate at which it loses speed is known (as it is); all that is necessary is to make the graduations of the scale correspond to the variations in the speed of the spot. It is, however, possible to make the increase of potential on the X_2 plate and the rate of travel of the spot uniform by the use of specially designed circuits if it is necessary to do so for a particular purpose.

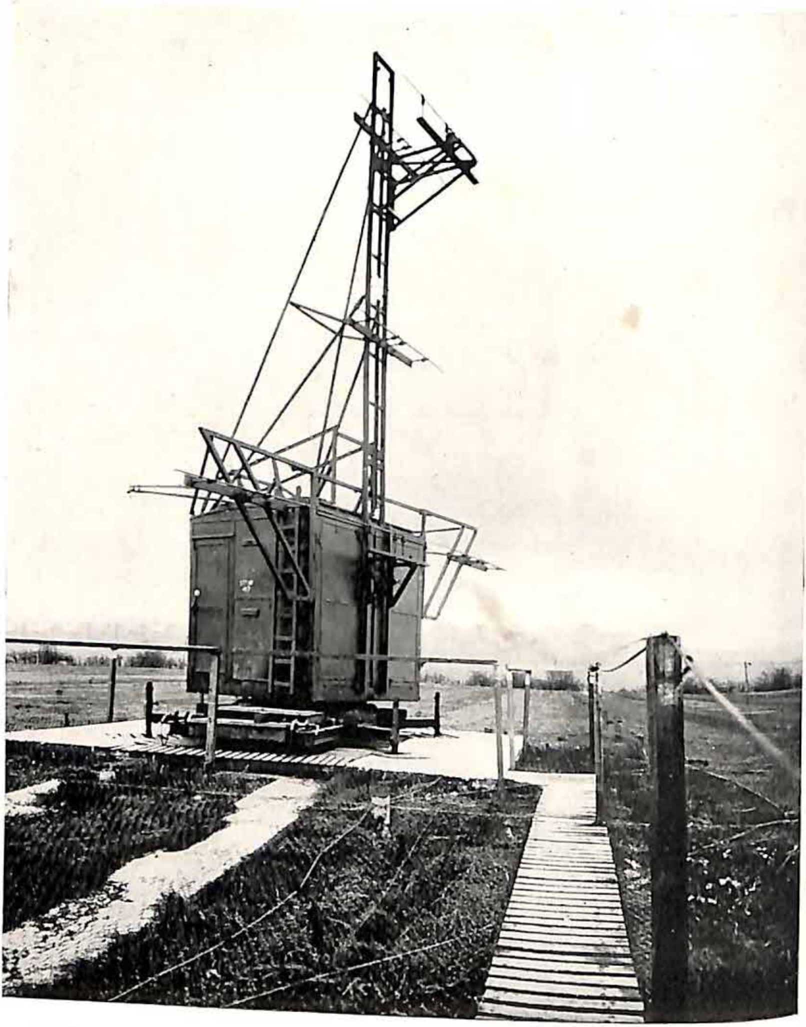
An inflated tyre can be emptied very quickly of air by removing the valve and so providing a large exit through which the pent-up air can rush with little opposition. The emptying process is also very rapid at the start, when there is a high internal pressure to drive out the air; but here again there is a tailing off as less and less pressure becomes available to expel what air remains.

A condenser, too, can be discharged very rapidly by the provision of a low-resistance path for the electricity stored up in it. Here also, the "emptying" starts with a rush, as the pressure within drives out current, and the same tailing off is found as the pressure drops. A rapid discharge of the time base condenser is brought about when the spot reaches the end of its travel and as the potential on the X_2 plate is removed it may fly back in possibly so short a time as a single microsecond to its resting place.



Compare the picture that the navigator sees by H_2S with the actual map. The circle on the map indicates the area covered by the H_2S picture. (*Official photograph. Crown copyright reserved.*)

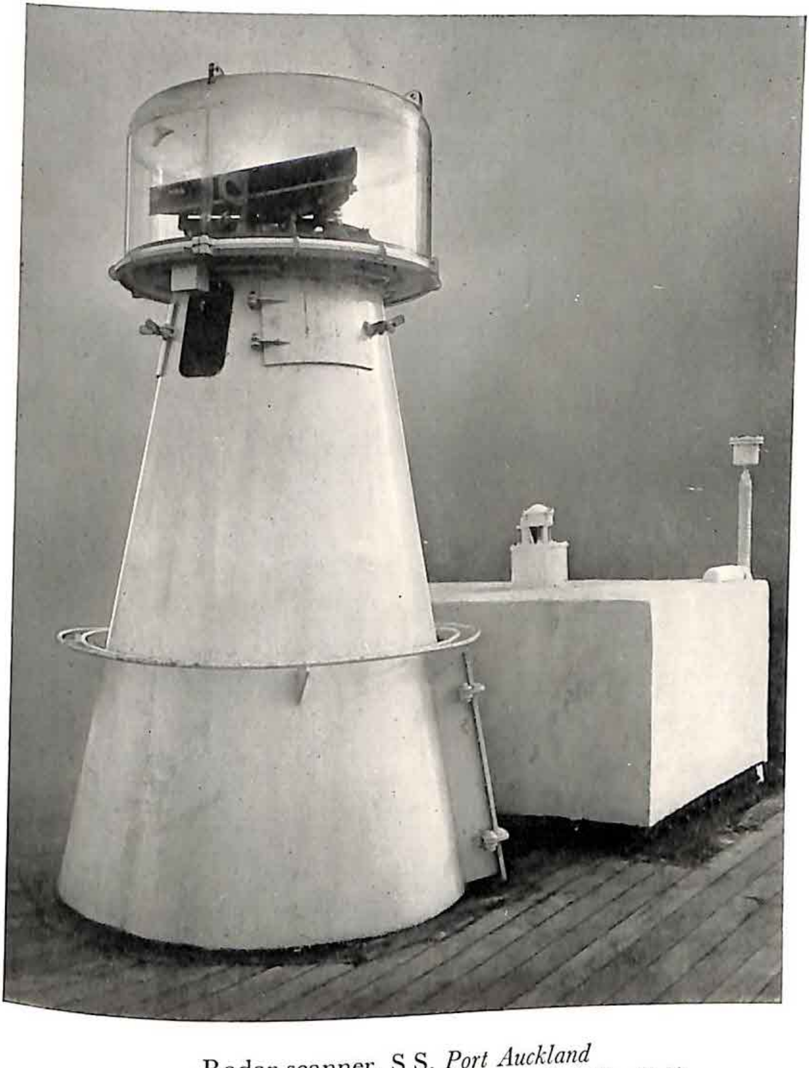
PLATE I



G.L. (Gun-laying) Radar. The receiver of a wartime equipment used on all A.A. gun sites. The cabin swings round on a pivot and is kept pointing at the target. The three sets of aerials are used for the measurement of range, bearing and angle of sight. This receiver was surrounded by a large "mat" of wire netting to ensure that the surface all round it was level.

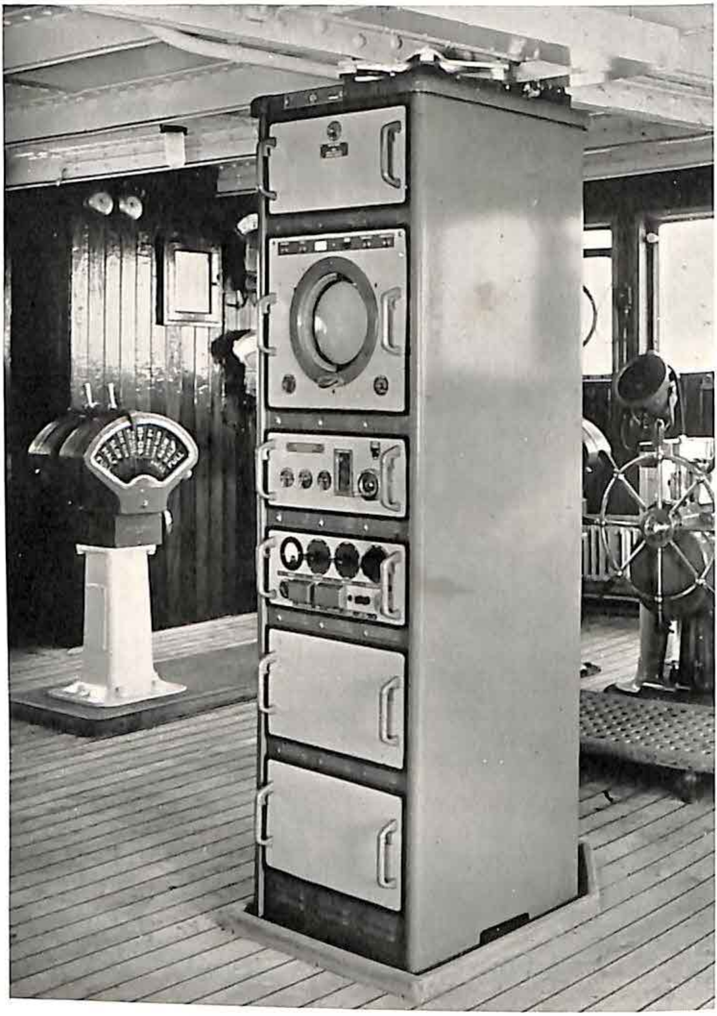
(*Official photograph. Crown copyright reserved*)

PLATE II



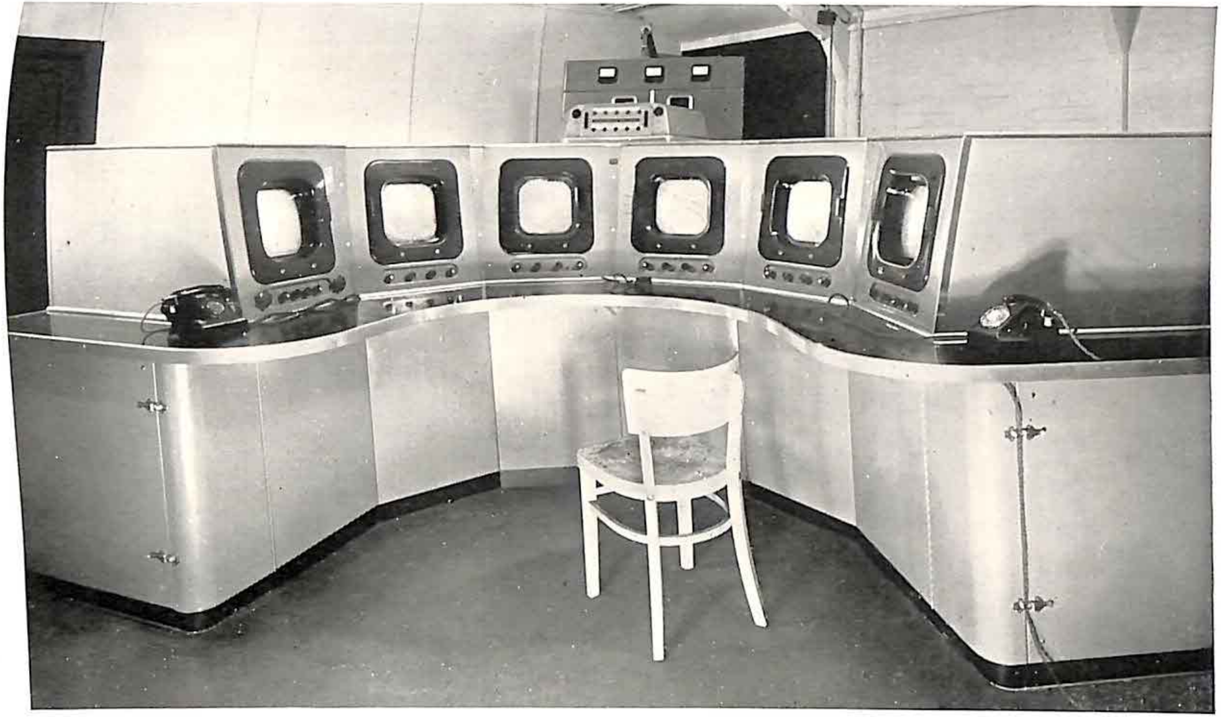
Radar scanner. S.S. *Port Auckland*
(*By courtesy of Metropolitan-Vickers Electrical Co. Ltd.*)

PLATE III



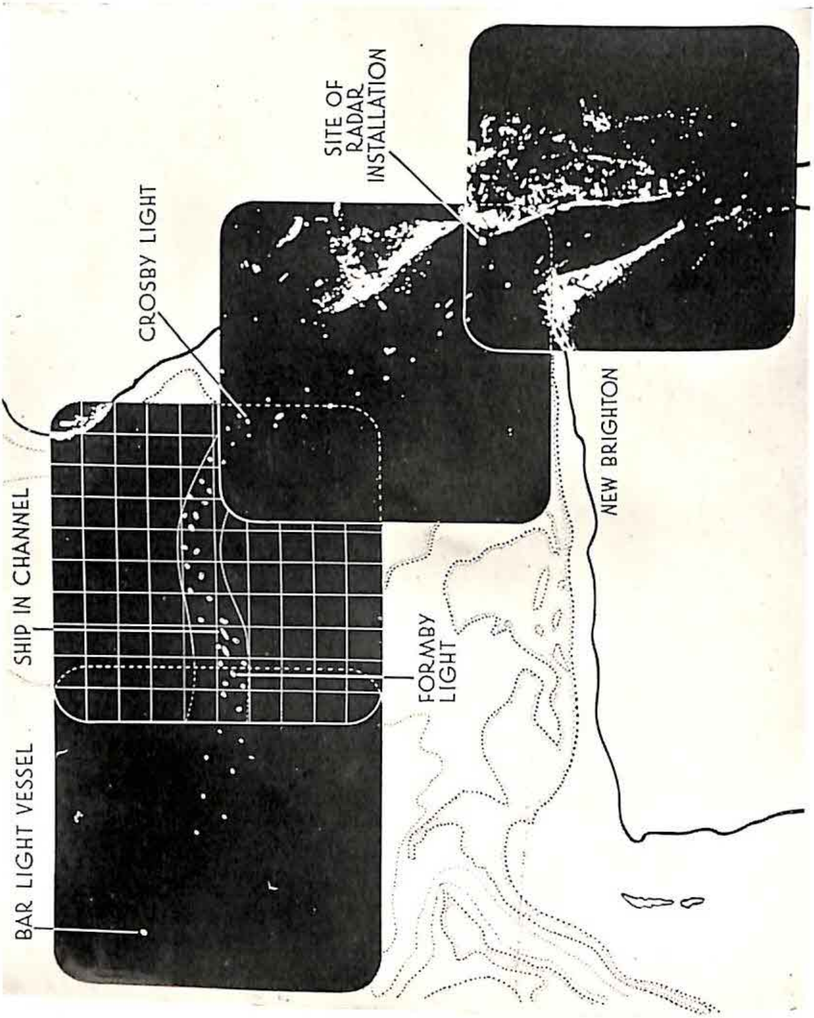
Radar console in wheelhouse of R.M.S. *Queen Mary*
(By courtesy of Metropolitan-Vickers Electrical Co. Ltd.)

PLATE IV



Liverpool Harbour Radar. The display console
(*By courtesy of The Sperry Gyroscope Co. Ltd.*)

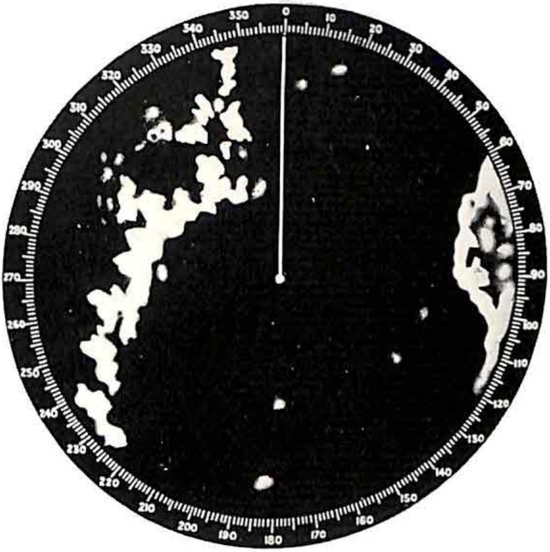
PLATE V



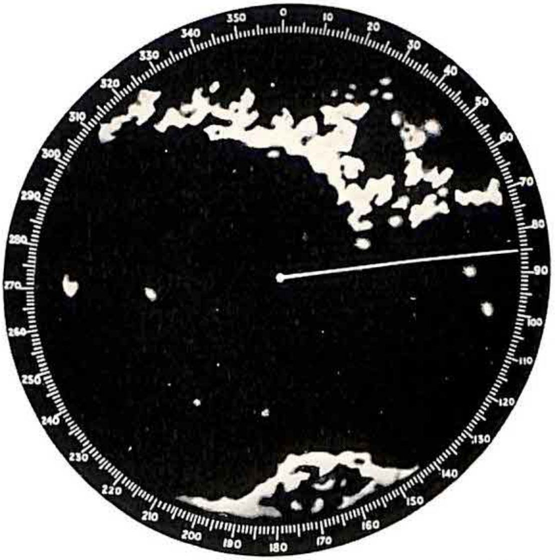
The radar picture of the Mersey Channel as shown on four P.P.I. screens

(By courtesy of The Sperry Gyroscope Co. Ltd. and "Discovery")

PLATE VI

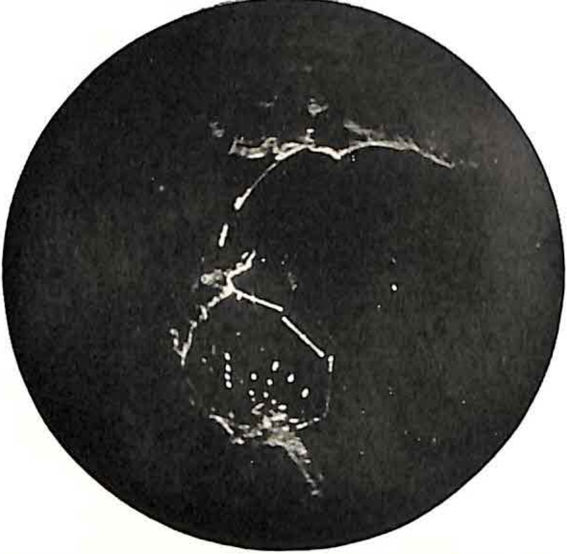


(*a*) P.P.I. picture with relative position

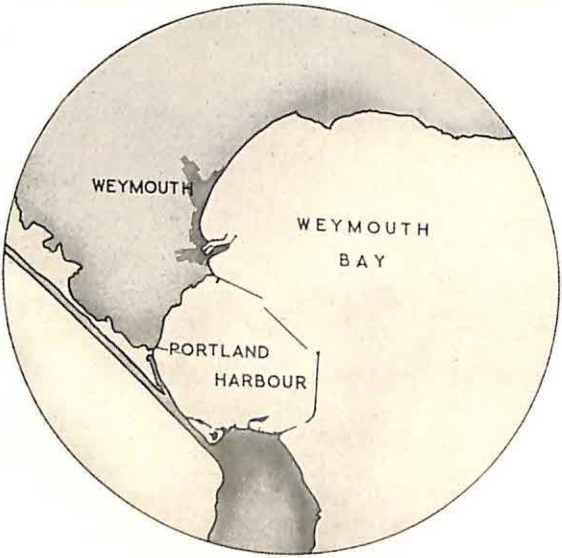


(*b*) The same picture with stabilised position
(*By courtesy of Kelvin & Hughes (Marine) Ltd.*)

PLATE VII



(*a*) The approach to Weymouth Bay and Portland Harbour as seen on the P.P.I. screen



(*b*) Compare the radar picture at (*a*) with this chart

(*By courtesy of Kelvin & Hughes* (*Marine*) *Ltd.*)

PLATE VIII

In Chapter III we saw that echo-ranging by sound waves on a fast moving object would not be a satisfactory business even if some means could be found of ensuring the arrival of detectable echoes from small targets at considerable distances. A directly approaching aeroplane twenty miles away when the direct sound pulse was sent out would, if travelling at 200 miles an hour, move over eight miles before the return of the echo. For defence purposes any such system would be of little use even with aeroplane speeds of 200 miles an hour: gunners require not the *past*, but the *present* range in order that the *future* range (that is, the range at the moment when the shell has made its upward flight to the target) may be worked out by that wonderful instrument the predictor. If the aeroplane of the future travels at 800 miles an hour, the sound echo from a directly approaching target would return some time after it had passed overhead!

Let us take the same problem that we investigated in Chapter III, the aeroplane approaching directly at 200 miles an hour at a distance of 20 miles, and see how far it has travelled whilst a wireless pulse goes out to it from the radar transmitter and the echo pulse returns from it to the receiver.

In round figures—this is a useful thing to remember—one yard a second equals two miles an hour. A sprinter who covers 100 yards in 10 seconds averages 10 yards in one second and his speed is therefore just about 20 miles an hour. Working the formula backwards, an aeroplane travelling at 200 miles an hour moves 100 yards a second.

As we have seen, the time for the out-and-return journey of radar echoes is 10.7 microseconds for each mile of range. For a range of 20 miles, therefore, the time is 214 microseconds. The 200 m.p.h. target covers 100 yards, or 3,600 inches in one second; 36 inches in $\frac{1}{100}$ second, 3.6

inches in $\frac{1}{1000}$ second or 0.0036 inches in one microsecond. In 214 microseconds its travel is 214 × 0.0036 – a little more than three-quarters of an inch. A 400-miles-an-hour modern fighter, radiolocated at 20 miles, approaches less than two inches whilst the direct pulse is going out and the echo returning. Even the 800-miles-an-hour aeroplane of the future will travel under a yard whilst a radar station *two hundred* miles away sends out its ranging pulse and receives the echo.

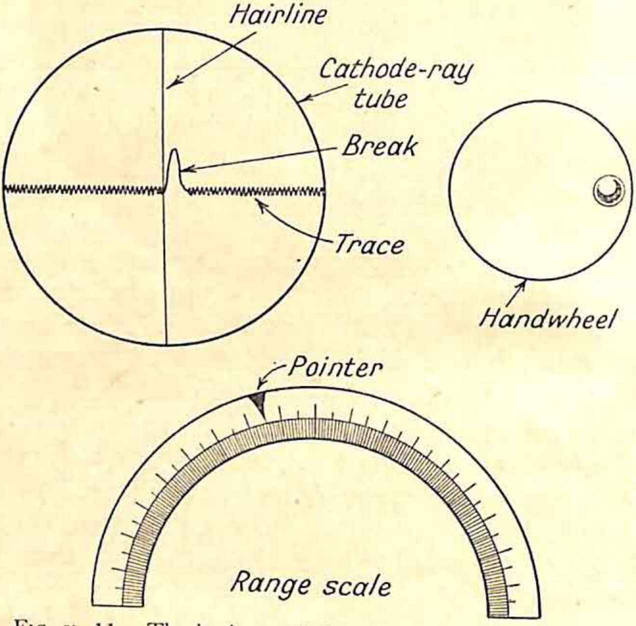


FIG. X. 11.—The business of the radar range operator is to keep the break on the hairline of the cathode-ray tube by using his handwheel. The pointer of the range scale then indicates the range.

The operator engaged in measuring range with a radar set has in front of him (Fig. x. 11) the screen of a cathode-ray tube, from 6 to 10 inches in diameter, on which his eyes are fixed; his right hand manipulates either a handwheel or a large knob; a little way from the screen of the cathode-ray tube there is a range scale, over which a pointer moves as the handwheel is turned. The position of the break is also controlled by the movements of the handwheel. The range operator's job is to keep the start or ONSET of the break on the hairline as shown in the drawing. So long as he does that the range scale records the accurately measured range of the target.

That sounds simple enough, though actually to keep the break due to a fast-moving target dead on the hairline demands a good deal of skill, which can be acquired only by practice. It is a curious fact that the simpler you make the controls of any piece of electrical or mechanical apparatus, the more complicated certain unseen parts of the "works" must necessarily become. Pre-selector gear change in a motor car is one example and "press-button" tuning in a radio receiver is another.

In the radar set the range-measuring devices are somewhat complicated, as might be expected from the beautiful simplicity of their controls. If, though, you keep in mind what we have seen about the time constant of a circuit consisting of a condenser and a resistor connected in series, I do not think that you will find it at all difficult to grasp the general principles of radar range measurement. Remember that to measure range by radio echoes we have to time the out and home journey of the pulse; remember, too, that the charging rate of a condenser gives us a means of making events occur at intervals of time which are minutely accurate.

The essence of range measuring technique is that the operator must always keep the onset of the target break on the hairline. Suppose that when he looks at the tube he sees a break at *A* in Fig. x. 12. All that he has to do is to turn the handwheel anticlockwise; the break then moves to the left and eventually reaches position *B*, when it is on the hairline. The pointer of the range scale also moves, for it is connected through gears to the handwheel. What is the operator really doing to the "works" when he turns his handwheel?

We know (1) that the X_1 plate has a fixed positive potential in order to make the spot start its journey from near the left hand edge of the screen (Fig. IX. 8); (2) that the spot is at the mid-point of the trace when the positive potential on X_2 equals that on X_1; (3) that the time base unit causes a continually increasing positive potential to be applied (Fig. x. 4) to X_1 during the passage of the spot across the screen.

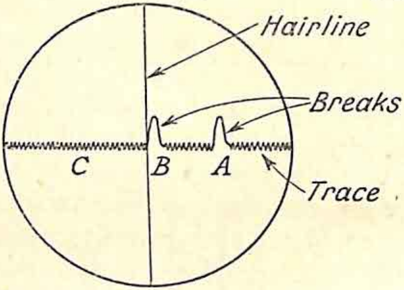


FIG. x. 12.—In measuring range the break is made to move until it occurs at the hairline. If it is at A, C or D the range handwheel is turned so as to bring it to B. The correct range is then recorded, as explained in the text.

An important part of the time base unit is a condenser and resistor circuit like that of Fig. x. 8. The X_2 plate of the cathode-ray tube is connected to the positive plate of the condenser; the positive potential of this plate increases as the condenser charges through its resistor. The rate at which the positive potential on X_2 grows thus depends on the time constant of the circuit. If the capacitance of the condenser is variable, the time constant, and therefore the rate at which the condenser charges, may be altered at will.

That is exactly what is done in the type of range measuring device which we are discussing. The condenser may be like that used for tuning an ordinary wireless set, having moving plates meshing with fixed plates. The capacitance of a condenser depends amongst other things on the area which the two sets of plates present to one another. When the fixed plates are fully meshed with the moving (as they are when you reach the longest wavelength covered by the tuning scale of a wireless receiver) the capacitance is at its maximum; it is at its minimum when the moving plates are completely disengaged from the fixed, as they are when you tune to the lowest wavelength of the scale.

Range measuring with the system described is in some ways very like tuning a wireless receiver. The tuning knob of a wireless set actuates the moving plates of the condenser through a geared-down drive; bringing the moving plates further into mesh with the fixed increases the capacitance and the wavelength to which the set is tuned. The tuning knob of a wireless receiver also causes a pointer to move over a graduated scale, whose markings are arranged to indicate, not the capacitance, but the wavelength to which it corresponds.

In the radar set the range handwheel controls the meshing of condenser plates. Through a train of reduction gearing it causes a pointer to move over a scale, or a scale to move past a fixed pointer. The graduations of the scale indicate, not the capacitance, but the range to which the apparatus is, so to speak, tuned.

Look again at Fig. x. 12. If the break appears in the position marked *A*, how can it be brought to the hairline? Clearly, if the break is at *A*, the time base condenser has charged to a potential a good deal higher than that on X_1 by the time that the pulse causing the break arrives on

Y_2. To make the break occur at the hairline we must so regulate the time constant that the condenser has charged only to the potential of X_1 when the break arrives, for the break will be on the hairline if the potentials of X_1 and X_2 are equal at the moment when it occurs. When the break is at *A* the condenser is charging too fast; we must slow down the charging rate, or increase the time constant; we can readily do by turning the handwheel so as to increase the capacitance. The larger its capacitance, the longer the condenser takes to charge to a given potential.

Similarly, if the break is seen at *C*, it occurs before the time base condenser has charged to the potential of X_1. The charging rate is too slow. We can speed it up by reducing the capacitance through a movement of the handwheel.

The adjustment of the capacitance necessary to make the condenser charge at such a rate that the break occurs at the hairline is translated on the scale into yards of range. The longer the range, the greater must be the capacitance of the time base condenser to bring the break to the hairline; the shorter the range, the smaller must be that capacitance. The pointer of the range scale responds to minute adjustments of the capacitance and thus records range with great accuracy.

This method of range measurement has another important consequence: a moving target may be followed, the handwheel being turned at the rate necessary to keep its break on the hairline. The changing range is then continuously recorded by the gradual movement of the pointer over the range scale.

There are other methods of range measurement; in some, for instance, the capacitance remains fixed and the resistance is varied. They differ considerably in detail from one another, but the basic principle of all is the use of the time constant of a condenser and resistor circuit.

CHAPTER XI

Radiolocating

THE aerial of an ordinary wireless receiving set, or that of a radar receiver, performs very much the same function as the lens of the eye. The lens collects light waves and passes them on to the retina of the eye, where they are detected. From the retina they pass by way of the optic nerve to the brain, in which they produce the sensation that we know as sight. Similarly the aerial collects wireless waves and sends them on to the wireless detector. If the energy derived from these waves is very small, as usually it is, they may require magnification (or amplification, as it is called) before they are delivered to the detector. Similarly, the eye needs the amplification of a telescope to be able to deal with the light waves from very distant objects, or that of a microscope to be able to deal with objects that are close but minute.

The eye looks out for light waves: it will require no great stretch of the imagination to regard the wireless or radar receiving aerial as looking out for wireless waves.

The look-out or field of vision of the best of eyes is limited. You cannot see behind you and two simple experiments will show how restricted is forward vision. Close one eye first of all and with the other fix your gaze straight ahead on some object, such as a mark on the wallpaper if you are in the house, or a post, a chimney-pot or a distant tree should you happen to be out of doors. Now stretch out the arm corresponding to the open eye (right arm for right eye, left arm for left), raise the forefinger and swing it slowly round, keeping the eye firmly fixed on the chosen point and not allowing either it or the head to move. You will find that the finger cannot be seen when the arm is extended in line with the shoulder: it comes into view as the arm moves somewhat forward of that position and disappears after the arm has moved across in front of the eye and the line of sight is cut off by the nose. The shape of the look-out or field of vision is very much as shown in Fig. XI. 1.

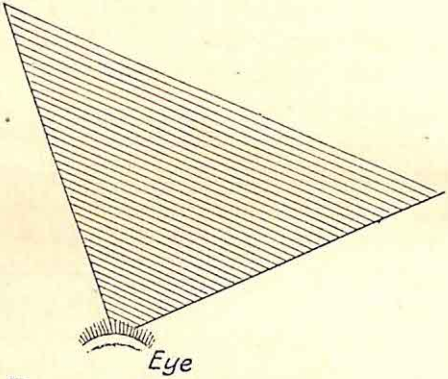


FIG. XI. 1.—The horizontal field of vision, or look-out, of the right eye.

The second experiment is again made with the eye firmly fixed on a mark and a moving forefinger held at arm's length. This time, start by holding the finger directly between the eye and the mark, when you will easily see every detail of the ridges and whorls on the skin that go to make a fingerprint. Now move the finger slowly to the right or left, being very careful not to let the eye move with it. When it has moved but a short distance, you will notice that, though it is clearly seen as a finger, the small details are no longer visible: to see them you must turn the eye until it is looking straight at the finger. From this we may judge that by far the most acute portion of the field of vision is a narrow section immediately in front of the eye. The shape of the field of vision of the right eye can be drawn as shown in Fig. XI. 2, where the length of the lines radiating from the eye is proportionate to the acuteness of vision in any direction, the eye itself being fixed and looking straight forward. By drawing a curve round the ends of the radiating lines we obtain a figure like that shown in the drawing. Such a figure is known as a POLAR DIAGRAM, and polar diagrams can be drawn for aerials as well as for eyes: for receiving aerials they show the degree of acuteness or efficiency in any direction. Note that such a diagram is not concerned with physical distances. It does not matter whether the eye in Fig. XI. 2 is fixed on a full stop on a printed page some fifteen inches away or on a star, whose distance may be measured in millions upon millions of miles. The length of the line *a*, *b* indicates that the greatest acuteness of vision is directly to the front of the eye and this acuteness falls off in a manner proportionate to the lengths of the other radiating lines.

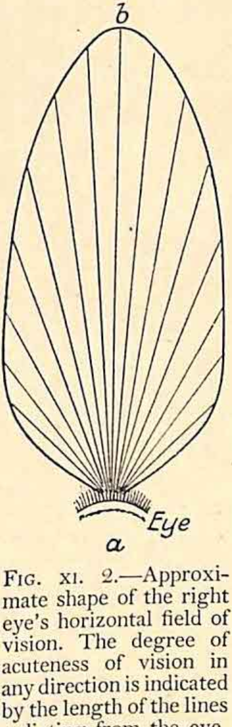


FIG. XI. 2.—Approximate shape of the right eye's horizontal field of vision. The degree of acuteness of vision in any direction is indicated by the length of the lines radiating from the eye.

Remembering the discussion in Chapter II of the directional properties of a portable wireless set containing a frame aerial, we can indicate the look-out of such an aerial in the way shown in Fig. XI. 3, or we can show the intensity of its look-out in any direction by drawing the polar diagram of Fig. XI. 4. This shows that it receives most strongly when it is on a line to the transmitting station, that signal strength falls off as it is turned to right or left and that minimum signal strength occurs when the aerial is so turned that it lies at right angles to the line transmitter-receiver.

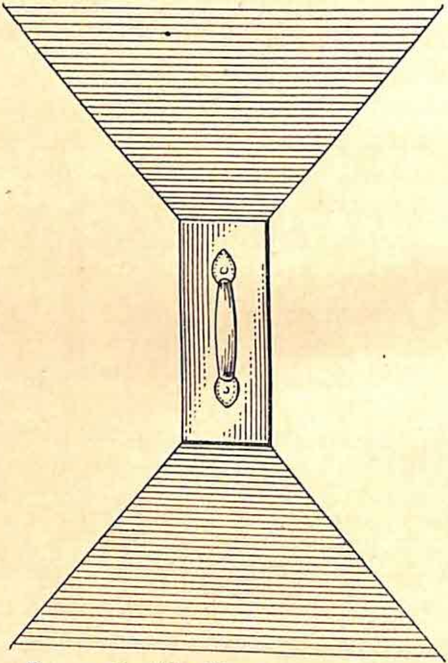


FIG. XI. 3.—The "Look-out" of a portable wireless set.

The ordinary outdoor aerial erected for broadcast reception looks out almost equally well in all directions: there is no very noticeable difference in signal strength if stations at equal distances and using equal power, lying to the North, South, East or West are tuned in. Its polar diagram could be represented approximately by a circle. But different kinds of aerials and combinations of several aerials working as a team may have look-outs and polar diagrams of a large variety of kinds.

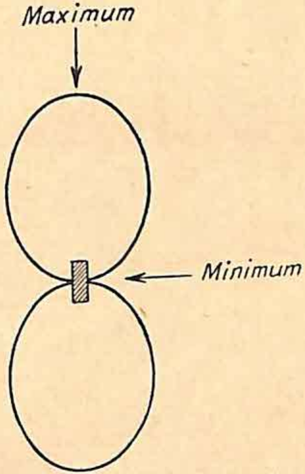


FIG. XI. 4.—The shape of a portable wireless set's look-out drawn as a polar diagram.

In radar equipment the type of aerial generally used is that known as a HALF-WAVE DIPOLE: like so many scientific mouthfuls, this name ceases to be forbidding when we come to see why it is chosen. The aerial is called half-wave (Fig. XI. 5), because it is approximately half-a-wavelength long overall: thus if the wavelength in use is five metres, the overall length of the corresponding half-wave aerial is just under two and a half metres. The telescopic portions shown in Fig. XI. 5 may be fitted to enable the aerial to be lengthened or shortened to match the

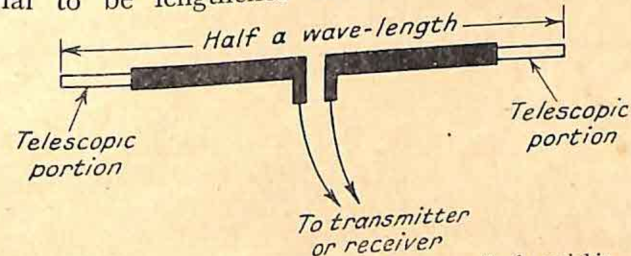


FIG. XI. 5.—As its name implies, the half-wave dipole aerial is approximately half-a-wavelength long and it has two poles or ends. The use of the telescopic portions is explained in the text.

wavelength in use. The aerial is called a dipole, because it has two poles or ends. If one half-wave dipole, erected horizontally, is used all by itself, its look-out is shaped very much like that of the frame aerial of the portable set, which is illustrated in Figs. XI. 3 and XI. 4. There is, however, this difference: whereas the frame aerial of a receiver gives maximum results when it is pointing towards the transmitting station and minimum results when it is turned at right angles to this direction, the single half-wave dipole behaves (Fig. XI. 6) in precisely the opposite way. Turn it so that it lies at right angles to the line

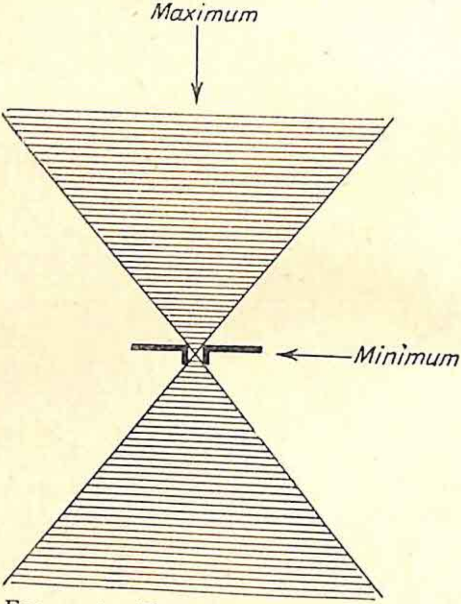


FIG. XI. 6.—The look-out of a half-wave dipole is much the same shape as that of the frame of a portable set. But unlike the frame, it shows maximum efficiency when pointing at right angles to a line joining transmitter and receiver.

transmitter-receiver, and maximum reception is obtained. The minimum occurs when it is turned to the position which gives maximum reception with a frame, that is when it lies along an imaginary line joining transmitter and receiver.

It will be seen at once that, like the frame of the portable set, a single half-wave dipole could be employed to give an indication of bearing by making use of one of the minima: when it produced the smallest signal or no signal at all it would be pointing straight at the target. If it were used in this way it would give only very rough bearings, for the minimum is not sharply defined; that is, the aerial can be turned several degrees in either direction without there being any noticeable difference in the reception. The maximum is used in certain cases for obtaining rough preliminary bearings on a distant target, but neither it nor the minimum can supply anything like accurate bearings.

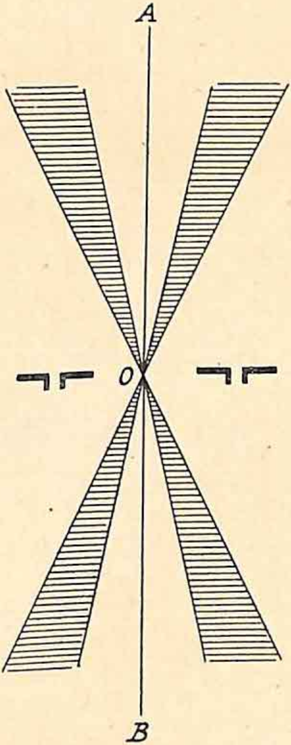


Fig. xi. 7.—A combination of two half-wave dipoles can be made to have a look-out of the kind shown above.

Half-wave dipoles can be worked not just singly, but in teams (or ARRAYS, as they are called), and in this way a large variety of different look-outs can be obtained. If, for example, two of these aerials are used together in a certain way the look-out of the combination is as shown in Fig. xi. 7.

It will be seen that we have a sharp minimum forward on the line *O-A* and another to the rear on the line *O-B*. A slight turning of the pair of aerials to right or left produces a pronounced difference in reception.

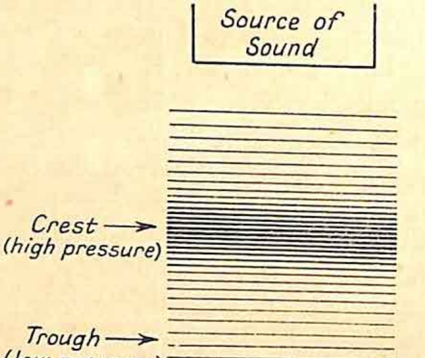


FIG. XI. 8.—The head is not directly facing the source of the sound waves, but has been turned to the right. The crest of the leading wave has only just reached the right ear, but it has passed the left ear, which is being approached by the trough.

The method of measuring bearing by means of an array of two aerials is most easily explained by an analogy with the co-operation that exists between the ear and the eye. Have you ever thought how or why it is that you automatically look in the direction of any sound which attracts your attention? It is probably a survival of one of the oldest of instincts: to save themselves from becoming the prey of larger and better armed animals our remotest ancestors had to be pretty quick in discovering whence came the sounds that gave warning of danger. The ears received the ominous sounds and passed their message to the brain, which instantly told the eyes where to look. But how did the message sent by the ears to the brain unfailingly indicate the right direction? As a matter of fact, when a sound is heard it is to the ears that the brain gives its orders; they are told to indicate when the head is moved enough to right or left to make the sound as strongly heard by one as by the other. As the eyes are also part of the head they must be looking in the proper direction if the ears signal the brain to stop the head moving at the right moment.

Fig. XI. 8 will help to explain how with the help of the ears the head can be turned so as to face the direction from which a sound is coming. In the drawing a train of sound waves is shown travelling from its source and reaching the ears of a listener, who has turned his head slightly aside and is not facing exactly in the direction from which the sound comes. It will be seen that in the position shown the waves have a little farther to travel to reach the right ear than to reach the left. These airborne waves consist, as we saw in Chapter III, of high-pressure crests followed by low-pressure troughs. In the drawing the crest of the leading sound-wave has only just reached the right ear; but it has passed the left ear, which is already being approached by the trough.

As the ear drums are pressed in by the high-pressure crests and pulled outwards by the low-pressure troughs it is clear that those belonging to the head in the drawing cannot be vibrating exactly in time with one another: when the right drum is fully pressed in the left has moved some little way outwards. The waves, in a word, are not being received exactly "in step" by the two ears.

When the head is so turned that it is directly facing the source of the sound, both ears are at exactly the same distance from that source. Crests reach the right ear and the left at the same instant and both drums vibrate together. The waves are now arriving "in step." In technical parlance, waves arriving so that the crest coincides with crest and trough with trough are said to be IN PHASE; when they do not so arrive thay are OUT OF PHASE.

The brain detects at once that the sound waves are reaching the ears out of phase if the head is not facing their source and orders the head to move until their arrival in phase is ensured by making each ear equidistant from the source of the sound. When that has been done, the eyes are looking towards the place from which the sound is coming.

Much the same thing can be done by using two aerials, in line with one another but some distance apart, in the radar receiver. When they are swung so as to face the target from which the echo pulse returns, both are equally distant from the target and the wireless waves of the pulse are received in phase. But if the aerials are moved so as to face a little to the right or to the left of the target the waves are no longer received in phase: the greater the error in the alignment of the aerials, the more out of phase is the arrival of the waves. The brain in this case is a cathode-ray tube and unmistakable indications upon its screen show the operator who is measuring bearing how the aerials must be turned in order to make them face the target and give in-phase reception of the oncoming echo from the target. A slightly different method is used when it is desired to make the reception of a minimum signal indicate that the radar receiver is pointing directly at the target. Here the aerials are so arranged that when the apparatus is aligned on the target one delivers to the receiver a "push" corresponding to the crest of a wave at the instant when the other delivers a "pull" corresponding to a trough and *vice versa*. Thus when the receiver is on the correct bearing, the crests and the troughs cancel out and no signal is delivered from the bearing aerials.

So far so good; but like the frame aerial of the portable set, this team of half-wave dipoles has the same look-out to the front as to the rear. A target at *A*, in Fig. XI. 9, would produce exactly the same reception as one at *B*. How can we find out in which of these two directions the target is? Fortunately there are simple means of making this unmistakable. Two methods are, in fact, available for checking the look-out direction and we can take our choice. For either a single half-wave dipole is used, which gives maximum reception (Fig. XI. 6) when pointing at right angles to a line target-receiver. In the first method a device is brought into action by a switch which intensifies the forward look-out (Fig. XI. 9 (*a*)). If the target is in front a stronger signal is received and the break on the cathode-ray tube due to the echo from the target (Fig. x. 6 grows taller when the device is switched in. The second method is similar, but here the break is made to decrease in size if the radar set is pointing towards the target, or is looking out in the correct "SENSE," when the switch is flicked on.

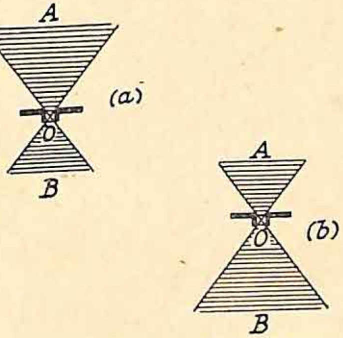


FIG. XI. 9.—Two methods of determining whether the target is in front or behind. A (*a*) a single half-wave dipole is made more sensitive forward (*O A*) than rearward (*O B*). At (*b*) just the opposite is done by a different method. The text explains how either method of determining "sense" can be employed.

The aerials used in one war-time equipment for the measurement of bearing and for checking sense can be seen in Plate II. Attached to the "wings" jutting out from opposite ends of the cabin are the two bearing aerials.

Near the top of the ladder is the upper elevation aerial and in front of this is a bracket on which is mounted a screening aerial, which can be brought into or out of use at will by means of a switch inside the cabin. With the screen switched out of action the look-out of the upper elevation aerial is as in Fig. XI. 6. Switching in the screen gives a look-out like Fig. XI. 9 (*b*). Thus, if the sense is correct, the target break becomes smaller when the screen is switched into action.

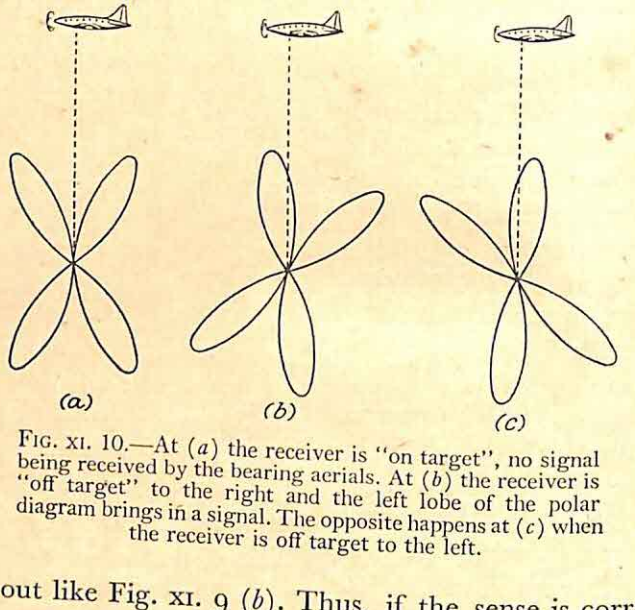


FIG. XI. 10.—At (*a*) the receiver is "on target", no signal being received by the bearing aerials. At (*b*) the receiver is "off target" to the right and the left lobe of the polar diagram brings in a signal. The opposite happens at (*c*) when the receiver is off target to the left.

This method of bearing measurement with an array of two half-wave dipoles arranged to give the Fig. XI. 7 polar diagram was used in earlier types of radar apparatus working on wavelengths between about 3 and 6 metres. It gives fairly good results; but its accuracy cannot approach that of modern equipment working on wavelengths of 1-10 *centi*metres.

The whole cabin carrying the aerials giving the Fig. XI. 7 polar diagram is rotatable by the bearing operator. When it is correctly aligned (Fig. XI. 10 (*a*)) the bearing signal from the target is zero. If the operator is "off target" to the right (Fig. XI. 10 (*b*)), the left lobe of the polar diagram brings in a signal. Similarly, a signal is brought in by the right lobe (Fig. XI. 10 (*c*)) if the operator is off target to the left.

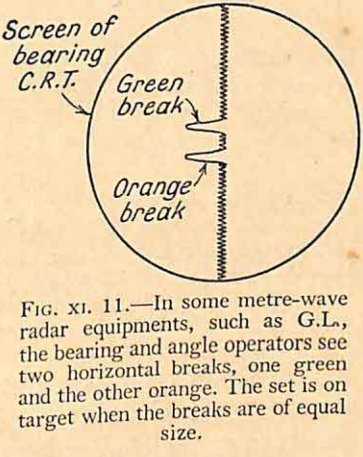


FIG. XI. 11.—In some metre-wave radar equipments, such as G.L., the bearing and angle operators see two horizontal breaks, one green and the other orange. The set is on target when the breaks are of equal size.

By means of electrical devices and an ingenious mechanical switching arrangement two horizontal breaks are made to appear on the bearing C.R.T. as shown in Fig. XI. 11. A rapidly rotating disc causes a green window to be "cut in" when the upper break appears and an orange window when the lower appears. The disc revolves so rapidly that the operator sees simply a green break above the middle of his tube and an orange break below it. The green break represents the signal brought in by the range aerial added to that brought in by the bearing aerials; the orange break is the range signal with the bearing signal subtracted from it.

If the operator is on target (Fig. XI. 10 (*a*)) the bearing signal should be zero. In that case the green break is the range signal *plus* nothing and the orange break is the range signal *minus* nothing. The two breaks are thus equal, since both represent the same thing. When, however, the operator is not properly on target there is a bearing signal (Fig. XI. 10 (*b*) and (*c*)) and one break is larger than the other. The operator's task, then, is to keep the two breaks equal in size by movements of his crank or handwheel. So long as they are equal he is on target. Further, he can tell from the coloured breaks whether or not the "sense" is correct; if it is, swinging off-target to the right makes the green one increase and the orange one grow smaller.

A similar arrangement is used for the measurement of angle. Again there is a team of two aerials, the upper elevation aerial and the lower elevation aerial. For measuring angle of sight use is made of the vertical look-outs of these. The angle operator also sees green and orange breaks on his C.R.T. screen and must keep them equal. If he does so the correct angle of sight is recorded on the angle scale.

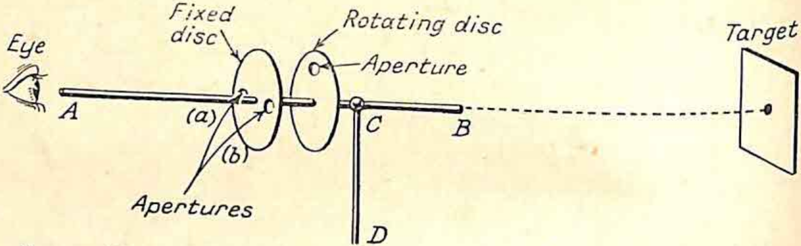


FIG. XI. 12.—*A B* is a horizontal rod, pivoted at *C* to a vertical support, *C D*. On the rod is a fixed disc with apertures at "9 o'clock" and "3 o'clock" and a rotating disc with a single aperture. As the rotating disc revolves the apertures in the fixed disc are alternately opened and closed.

Another interesting way in which a bearing may be obtained from the radio echo returning from the target may also be outlined—again it is necessary to stress the usefulness of regarding the aerials of the radar receiver as looking out, for this method is most easily understood from analogies with vision.

In Fig. XI. 12 *A-B* represents a horizontal rod pivoted on the upright support *C-D*. Two discs are mounted on *A-B*. One is fixed and has two apertures, at "9 o'clock" and "3 o'clock" respectively. The second disc is rotating rapidly. It has a single aperture which once in every revolution coincides with each of the apertures in the fixed disc in turn. The effect to an eye placed at *A* is that the apertures in the fixed disc are alternately opened and closed. Look now at Fig. XI. 13, which shows the same apparatus as seen from above. When (*a*) is opened by the revolving disc the field of vision is to the left of the target; it is to the right when the revolving disc opens (*b*). If the eye is kept at *A*, can the rod be made to point towards the target? It can, as Fig. XI. 13 indicates. Since the revolving disc is turning rapidly, the eye will form the impression that both apertures in the fixed disc are open all the time and that there is no interruption of its field of vision through them. Actually that field of vision is being switched first to the left and then to the right. So long as the horizontal rod is kept pointing straight at the target, the target does not come into the field of vision; it remains invisible. But if the pivoted rod is moved so that it points to the right of the target the latter comes into the field of

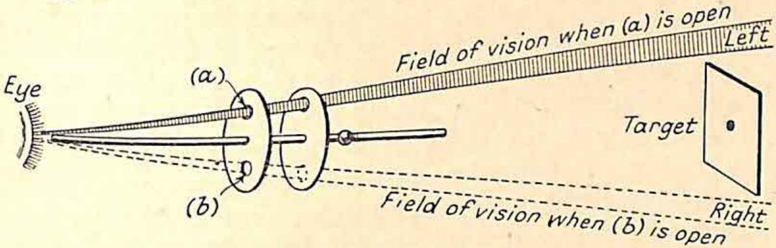

Field of vision when (a) is open
Left
Eye
(a)
Target
(b)
Field of vision when (b) is open
Right

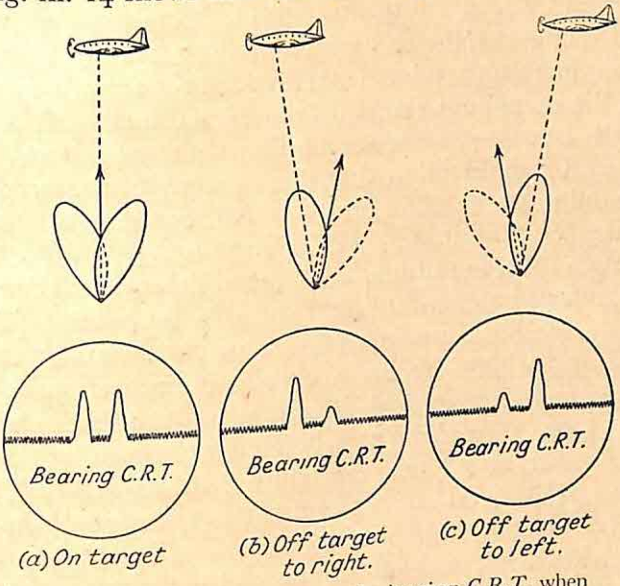
FIG. XI. 13.—Looking down on the apparatus from above. The field of vision is to the left of the target when the aperture in the revolving disc coincides with (*a*) and to the right when (*b*) is opened.

vision and is seen through aperture (*a*). Similarly a movement to the left off the correct line makes the target visible in (*b*). Any error is thus at once seen by the eye and by using the "minimum" between the two fields of vision in this way the rod can be kept pointing correctly even if the target is itself moving horizontally.

In the same way the look-outs of two aerials can be slightly splayed like the fields of vision in the drawings; and arrangements may be made to switch the aerials in and out of use alternately. Or the aerials may themselves be made to rotate rapidly. This is done in many centimetric radar equipments. The tiny aerials needed for waves 10 centimetres are less than two inches in length are placed at the focal point of a parabolic metal reflector, which acts in just the same way as that of a motor car headlamp or a bowl fire, forming the waves into a narrow beam. The look-out of the bearing-measuring part of the radar receiver can thus be made to flick from side to side and the apparatus is pointing in the right direction when the flicks take the aerial look-outs an equal amount to right and left of the target.

It is not difficult to see that apparatus similar to that illustrated in Figs. XI. 12 and XI. 13 but with a rod fixed horizontally and free to move vertically up and down could be made to point at a target some distance above the ground if the apertures were at "12 o'clock" and "6 o'clock." In this case the field of vision would be switched now above and now below the target: if the rod were pointed too low the target would appear in the top aperture; if too high, it would be seen in the bottom one. Similarly, one means of measuring the angle of sight is to switch in and out alternately aerials with look-outs above and below the radar target. Another is to make use once more of rapidly revolving aerials, throwing their look-outs round the target, so to speak. Again the adjustment is correct if the indications received by the operator show that at one flick the look-out of the aerials is as much above the target as the next flick brings it below.

Fig. xi. 14 shows how the rotating aerial, switched in



(a) On target

(b) Off target to right.

(c) Off target to left.

Fig. xi. 14.—The indications on the bearing *C.R.T.* when a centimetric radar equipment is on-target or off-target to one side or the other. The angle *C.R.T.* shows similarly whether the equipment is on-target, off-target above or off-target below.

at "3 o'clock" and "9 o'clock" enables bearing to be measured. The breaks due to the signals received in the two positions are slightly displaced from one another and appear side by side on the trace. When the equipment is correctly aligned (*a*) and on-target each signal is of equal strength and the breaks are of the same height. If the alignment is wrong the breaks become unequal (*b* and *c*) and indicate what must be done to bring the equipment on-target.

Angle is measured in exactly the same way from the "12 o'clock" and "6 o'clock" positions.

The methods used in metric radar—radar, that is, whose wavelength is measured in metres—enable bearing and angle of sight to be measured accurately to within about one degree of angle. With good centimetric apparatus the maximum errors do not exceed a few minutes of angle. In case you are not familiar with angular measurements I may mention that the diameter of the sun or of the full moon as seen from the earth represents about half a degree—30 minutes—of angle.

Such then, in outline, are some of the methods used for measuring bearing and angle of sight by radar methods. These methods are in many ways closely analogous to those by which the brain obtains its indications of the horizontal and vertical directions of an object with the aid of the eyes and the ears. Not a few electrical appliances are, in fact, attempts to reproduce as nearly as possible the wonderful operations performed by organs of the human body. The microphone, for instance, is a fairly close electrical copy of the mechanism of the ear and the telephone receiver is based on the way in which speech is produced by the vocal cords.

With a moving target, such as an aeroplane in flight, range, bearing and angle of sight are constantly changing. Radar can supply a continuous stream of accurate, up-to-the-moment information to the plotting room or to the predictor. Courses can thus be plotted and A.A. guns can engage distant and completely invisible targets in war. In peace aircraft may be guided through fog or darkness with accuracy and safety.

CHAPTER XII

Radiolocating—*continued*

WE have now seen something of the methods used in radar for measuring ranges. We have also seen how the look-out of the receiver can be concentrated on the target. The look-out may be directed horizontally so as to indicate in which direction horizontally the target is; it can also be adjusted vertically and used to measure the angle of sight to a target such as an aeroplane flying high above the surface of sea or land. The movements of the two look-outs (the horizontal and the vertical) are recorded on scales. By means of these scales the position of the horizontal look-out at any instant indicates the compass bearing of the target and that of the vertical look-out the angle of sight.

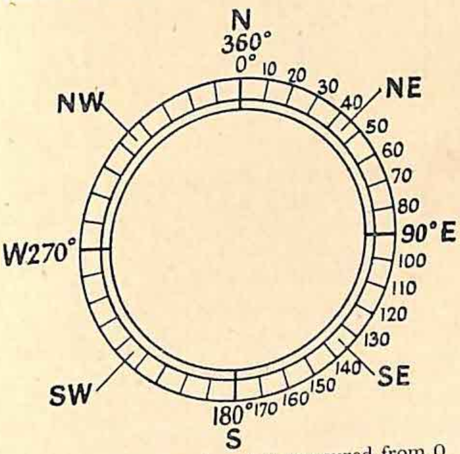


Fig. xii. 1.—Bearings are measured from 0 deg. to 360 deg. (North) clockwise round the circular scale. Thus East is 90 deg., South 180 deg., South-West 225 deg., West 270 deg., North-West 315 deg., and so on.

Fig. xii. 1 shows how the bearing scale is arranged.

Before radar equipment is brought into use it is first ORIENTED; that is to say, adjustments are made until the bearing scale reads 0 degrees or 360 degrees when the horizontal look-out is due north. It is more convenient and more accurate to graduate the scale in degrees from 0 degrees to 360 degrees than to mark it off into compass points. And there is less possibility of error: people have been known to mistake east for west, but even in the stir and excitement of battle it would be difficult to confuse 90 degrees with 270 degrees.

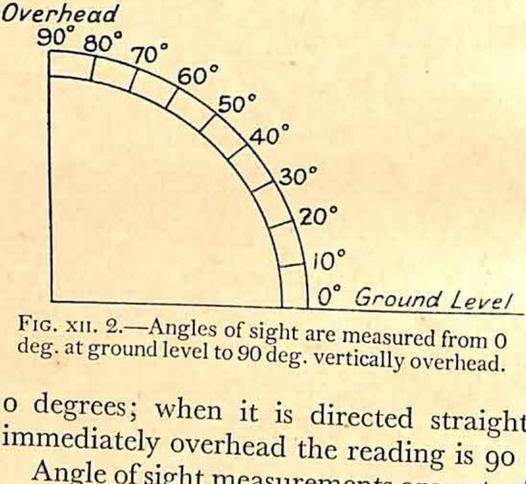


FIG. XII. 2.—Angles of sight are measured from 0 deg. at ground level to 90 deg. vertically overhead.

The way in which angles of sight are measured is shown in Fig. XII. 2. When the look-out is parallel with level ground the scale reads 0 degrees; when it is directed straight up at a target immediately overhead the reading is 90 degrees.

Angle of sight measurements are not, of course, required when radar is used at sea and the target is a coastline, an island, an iceberg or another ship. Both the measuring point and the target are then at the same level—the surface of the water—and the angle of sight between them is zero. When, however, the target is up in the air it is essential, as was explained in an earlier chapter, to be able to measure the angle of sight with considerable accuracy unless the equipment is being used purely for rough long-range indications.

At moderate and close ranges it is necessary to be able to plot the position of a target from moment to moment on a map. Now, a map has only two dimensions, length and breadth; the position of any point can be plotted on a map so long as we know its latitude and longitude, or its distance and bearing from a fixed point. But, as we have seen, to locate an aeroplane above the surface of land or sea we must work in three dimensions. We must have measurements of length (range), breadth (bearing) and height. It will be recalled that radar measures the slant, or line-of-sight range to a target (Fig. II. 3) and that to enable the point on the map which is immediately below the target to be marked in, the ground range must be known.

Fig. XII. 3 shows the principle of the instruments used for the automatic conversion of slant range and angle of sight into ground range and height. *A* is a scale of degrees, graduated from 0 to 90, which is fixed to the ground range arm *B*. Pivoted at *X* and free to move up and down is the slant range arm *C*. The height arm *D* is always vertical. but is free to move along the ground range arm. The whole apparatus is made to the same scale, say one inch equals 1,000 yards, but the height arm is marked off in feet (one inch equals 3,000 feet) since heights are always measured in feet. (In passing, it is perhaps rather typical of our peculiarly British habit of complicating measuring methods that our A.A. Artillery should use maps drawn to a scale of *inches* to the *mile* and divided into thousand-*metre* squares, whilst measuring its ground and slant ranges in *yards* and its heights in *feet!*) Suppose that radar equipment picks up a target at slant range 22,000 yards and angle of sight 20 degrees. The angle of sight arm is adjusted as seen in Fig. XII. 3 to cut the scale at 20 degrees. The height arm is then moved until its right edge meets the 22,000 yard mark on the slant range arm. The ground range can now be read off the ground range arm: approximately

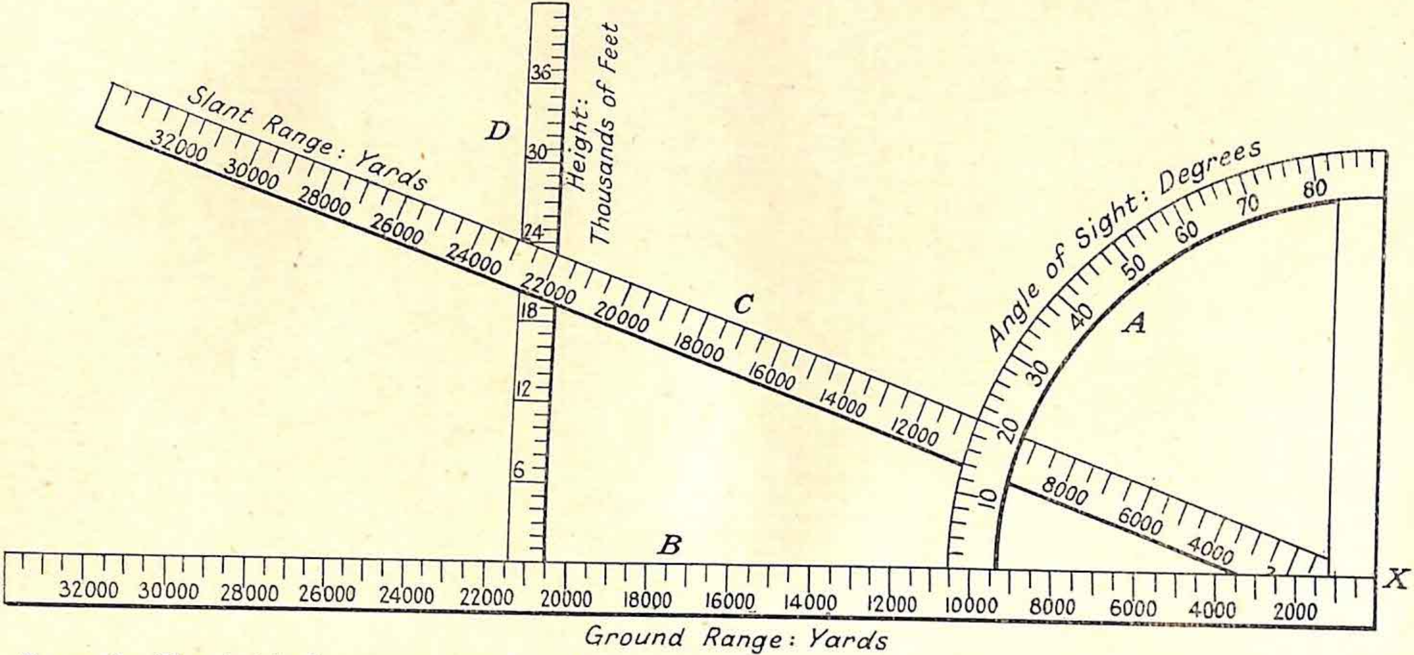


FIG. XII. 3.—The principle of range-converting gear. *A* is a scale of degrees fixed to the ground range arm *B*. *C*, the short range arm is pivoted at X. D, the height arm, is vertical, but free to slide along *B*.

20,500 yards. The upper edge of the slant range arm cuts the height scale at rather less than 23,000 feet and that is the height. With a small, rather crude instrument, such as that depicted in Fig. XII. 3, precisely accurate conversions to ground range and height could hardly be expected; the drawing, however, serves to show the general principle. The instruments actually used are more elaborate than this and give accurate results, but their operation is simple and quick.

Having received the information that the ground range of the target is 20,500 yards and its bearing, say, 294 degrees the plotter measures off 20,500 yards from his own position on the map on a bearing of 294 degrees and pinpoints the target, which is vertically above the mark that he makes on the map. If fresh bearings and ground ranges are supplied to him every few seconds his successive marks on the map indicate accurately the course that the target is taking. Its speed can also be obtained from the distance that it is found to travel in a given number of seconds.

Radar thus does more than merely locate a target by radio. It enables its course to be plotted and its speed to be ascertained. Should the target be a distant group of hostile aeroplanes warning can be sent in ample time to the areas for which the raid is making. When the raid is nearer, radar in combination with the predictor enables anti-aircraft guns to engage aircraft, which may be high above dense cloud. In similar ways the courses and speeds of enemy ships may be obtained by radar at sea—and remember that darkness, fog or falling snow make no difference to the clearness of its look-out. Not only does radar "see" at ranges far beyond those of the human eye; it can locate and follow targets when they are rendered invisible to the eye by conditions of light or weather.

Peacetime radar is concerned not with destroying aircraft, but with making their journeyings safe. As it enables their courses to be plotted accurately in all weather conditions and their positions at any moment to be known its value is inestimable. The controller on the ground can keep track of the planes which he is looking after and can let their pilots know exactly where they are whenever they require the information.

CHAPTER XIII

How it all began

AT the end of World War I, and indeed for some years after that, there were large gaps in our knowledge of the properties of wireless waves. Those with lengths below 100 metres were classed as short waves; the second category was that of the medium waves between 100 and 1,000 metres; the third, the long waves, from 1,000 to 5,000 metres; above these were the very long waves—a wavelength of 22,500 metres (about fourteen and a half miles) was used by one great commercial station in France.

It was believed at that time that the only way of securing reasonably reliable wireless communications with all parts of the world was to use enormously powerful stations, transmitting on very long wavelengths. It was categorically stated by more than one eminent man of science in the early nineteen-twenties that wavelengths below 100 metres could never be of any value for wireless communications.

At that time amateur wireless enthusiasts were clamouring for the allotment of wavelengths on which they could conduct experiments in radio transmission and reception without interfering with or suffering interference from the commercial stations and broadcasting stations, whose numbers were rapidly increasing. To still their clamour it was agreed by the authorities in many countries to make them free of a large part of the "useless" short waves. It was felt that this would keep them quiet in more senses than one and that they could do no harm by interfering with transmissions that really mattered on the higher and more useful wavelengths.

The amateur organisations accepted the allotment and settled down to make the best of the apparently meatless bone that had been thrown to them. It was not long before tales began to be heard of achievements that then seemed incredible. The amateurs were limited to the use of very small power in their transmitters. That and their restriction to the short waves, which the theories then current had "proved" to be valueless for spanning long distances, would surely prevent them from obtaining anything more than harmless amusement out of short-range wireless. But it did not. Reports that amateurs in this country were maintaining regular communication by wireless with others in France, Belgium, Holland and other Western European countries were found to have a solid foundation on fact. And no sooner had these unexpected reports been verified than there were fresh ones of messages exchanged with amateurs in Poland, Italy, Hungary. Then came still more astonishing rumours (discredited at first, but subsequently proved to the hilt) of successful communication with America. Most astounding achievement of all, an amateur, putting out from his transmitter not much more power than is needed to light the tail-lamp of a motor-car, proved beyond any possible shadow of doubt that his transmissions had been received intelligibly in New Zealand.

Clearly the short waves were not *quite* useless as wireless links over great distances. The professionals as well as the amateurs saw now that there might be something in them. Some who read this book may remember how in the early nineteen-twenties short-wave enthusiasts sat up night after night in the hope—sometimes realised—of receiving the first American short-wave broadcast transmissions to reach this country.

We have advanced a good deal since then! To-day the once despised short waves are amongst our most important means of long-distance communication. Had their possibilities not been realised and developed nothing like the vast system of world-wide radio telegraphy and radio telephony services that we now have could have come into existence; we could not have had high definition television or radar. Thanks largely to the work done by wireless amateurs, it was seen that feats actually achieved on the short waves made a revision of existing theories and beliefs necessary. Research went ahead in this new and promising direction and remarkable discoveries followed.

It had been proved some time previously that there is surrounding the earth, and high up in the atmosphere, a layer of air which acts as a reflector to certain wireless waves, bending them back to the surface of the ground. It is on account of this that stations on the broadcast band are heard at great distances by night: this Heaviside Layer, as it was named after its discoverer, is, for reasons outside the scope of this book, much more effective after sunset as a reflector of medium length wireless waves than it is by day.

Short waves were known to penetrate the Heaviside Layer and not to be reflected back to earth by it. But as short-wave transmissions were now being received at vast ranges, it seemed that there must be something, somewhere, which *did* send them back. Eventually the Appleton Layer, named like the first after the man who discovered it, was proved to exist and to reflect short waves. The average height of the Heaviside or E Layer is some 60-70 miles: the Appleton or F Layer is 140 to 200 miles above the Earth's surface (Fig. XIII. 1.)

It was Sir Edward Appleton who was the first to suggest in 1928 that the heights of the layers could be measured by "firing" wireless pulses vertically upwards and measuring the time taken by the echoes to return. The method was adopted and soon became of very great importance.

It had been found that the short waves had certain curious qualities: during one part of a 24-hour period transmissions on 30 metres might be heard from a far away station, though nothing could be picked up from other transmitters in the same part of the world which were using shorter wavelengths. Then the 30-metre station might begin to fail. Soon it would have become almost or even quite inaudible, whilst transmission on shorter wavelengths grew better and better. Daylight and darkness, the seasons of the year and sunspot activity were all found by experience to affect the optimum wavelength for transmissions between two places distant from one another.

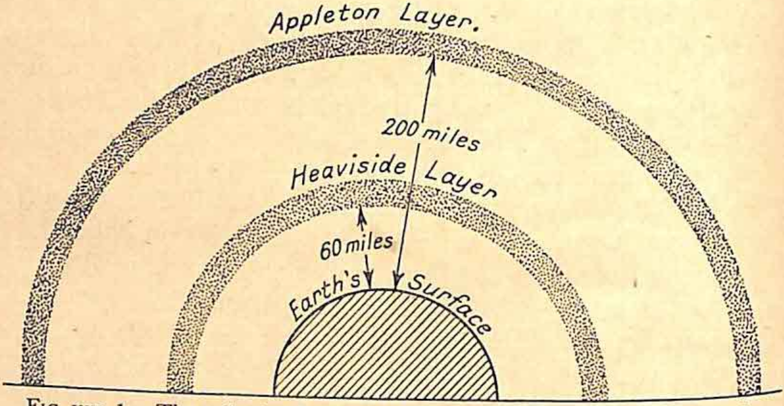


FIG. XIII. 1.—The reflecting layers in the atmosphere surrounding the earth.

If the short-waves were to be of value as a means of regular communication over long distances, it was clearly essential that there should be some reliable means of knowing in advance what wavelengths should be selected for good results at any time. It was found that the governing factors were the height and condition of the Appleton Layer, both of which varied considerably. These could be gauged by sending up wireless pulses of different wavelengths and measuring by means of the cathode-ray tube the heights from which their echoes returned. That part of the atmosphere in which the Heaviside and Appleton Layers are situated is known as the Ionosphere. Hence the process of testing the condition of the layers became known as IONOSPHERE SOUNDING. Before long observatories in many parts of the world were engaged in ionosphere sounding and their reports proved invaluable in enabling the optimum wavelength for any long-distance transmission to be selected.

The principle, as you will see, is exactly the same as that used for range measurement in radar. A pulse is sent vertically upwards and at 6.1 microseconds per 1,000 yards or 6.7 microseconds per 1,000 metres (you may recall that a metre is approximately a yard and a tenth) the height from which its echo returns can be measured with exactness. By sending pulses on various wavelengths and measuring the heights from which they are reflected, data can be obtained from which the optimum wavelength may be calculated for particular times and directions.

Along with ionosphere sounding there was another development. Amongst the greatest enemies of reliable communication on the short waves is the form of interference that we know as atmospherics. In Great Britain they are seldom severe, save in thundery weather, on the medium and the long waves; though all readers must be familiar with the unpleasant noises that they can cause. If atmospherics are strong the noises due to them may sound like the almost continuous tearing of pieces of tough fabric such as American cloth; milder atmospherics produce sounds reminiscent of the frying of bacon in a hot pan.

In some other parts of the world atmospherics are so severe that they may completely blot out transmissions. It was desirable to discover if possible any "hotbeds" of atmospherics in the world, so that these could be avoided in laying out the routes of short-wave communications. Thus was born the idea of locating the areas in which atmospherics mostly originated by means of receiving apparatus and, again, the cathode-ray tube was used. Much valuable work of this kind was done long before the war by Sir Robert Watson-Watt at the National Physical Laboratory. Here was developed a means of discovering at what range and in what direction lay the disturbance giving rise to any individual atmospheric. Incidentally, the bulk of those that annoy us in Great Britain originate in North Africa.

Meantime another development on quite different lines had been taking place. Pulse-sending wireless transmitting apparatus was installed in an aeroplane. It sent its wireless "Hi!" straight down to the ground, which reflected the pulse upward to receiving equipment. By timing (the cathode-ray tube again) the journey of pulse and echo the aeroplane could discover its exact height above the ground over which it was flying. This system was the direct ancestor of the absolute altimeter and of H_2S, both of which we shall discuss in greater detail in the next chapter.

By this time a new category of wireless waves had come to be recognised. These are the ultra-short waves, whose lengths are below ten metres. Such waves were required for the transmission of high-definition television. At first there were considerable technical difficulties about the transmission of such very short waves; but these were overcome. To-day there is yet another new category, the centimetric waves, or micro-waves—waves whose lengths are measured not in metres but in centimetres. Waves only a few centimetres in length are in use in modern radar apparatus and experimental work is actually in being on wireless waves one centimetre (two-fifths of an inch) or less in length. The frequencies of the ultra-short waves are staggering in comparison with those used for broadcasting. When the wavelength is ten metres, 30,000,000 complete waves, consisting of crests and troughs, occur every second and the frequency is said to be 30 megacycles a second. When we come down to one centimetre or less we are faced with frequencies of 30,000 megacycles and more.

For high-precision radar centimetric waves are used since they give the best echoes from such comparatively small targets as distant aeroplanes or ships. The research work done in the development of television was of considerable value to radar, for it led to simple but efficient methods of tuning in transmissions on such wavelengths. In the earlier forms of radar equipment ultra short waves were employed. It was realised that still better results and greater accuracy would be obtained if centimetric waves, which may be focused into a narrow beam, could be pressed into service; but until 1940 no means of sending out on such waves high-power pulses required for radar was known. In May, 1940, a wonderful new form of valve capable of generating high power on centimetric wavelengths was developed by Professor Randall and Britain again led the way.

This was the CAVITY MAGNETRON, whose working principles are explained in Chapter XVII; all that need concern us at the moment is that the magnetron, though small in size, enables pulses of very high power to be sent out on wavelengths of even one or two centimetres. With the first magnetron of 1940 a peak power of half a kilowatt was obtained on a wavelength of just under 10 centimetres. A kilowatt, by the way, is $1\frac{1}{3}$ horsepower. By 1946 British magnetrons were producing up to 2,500 kilowatts of peak power on centimetric waves. All of the latest and most accurate radar devices incorporate the magnetron.

The outline of the position a few years before the outbreak of the war was this. The ultra-short waves had been harnessed; the cathode-ray tube was in regular use for the measurement of the heights of the reflecting layers by means of wireless echoes. The sources of atmospherics were being located by measuring the range and the direction of the areas in which they originated, the cathode-ray tube being used as stopwatch and indicator. The idea of enabling an aeroplane to measure its height vertically above the ground over which it was flying by a wireless version of the marine echo-sounding principle had been born. It had also been observed that ultra-short wireless waves were "scattered" when they reached targets presenting an irregular surface, and that in such circumstances a minute echo returned to the sending point and could be detected if only sufficiently sensitive receiving apparatus and a sufficient degree of amplification could be contrived.

All of this was common knowledge to radio research workers of all countries in the early nineteen-thirties and appeared in the wireless text books of the day. Had you asked a scientist of, say 1935, who was thoroughly conversant with ultra-short wave technique so far as it had then progressed, whether it would ever be possible to locate a flying aeroplane or a warship at sea by wireless, he would probably have replied that he could see no good reason why this should not eventually be done. He would, though, in all likelihood have added that to make the necessary measurements, men with long laboratory training would be needed. If you had put a further question on the possibility of making apparatus for the purpose that could stand up to war conditions on sea and land, he might well have replied that exceedingly delicate instruments would be needed and that it was improbable that they would remain accurate—if indeed they continued to work at all—when exposed to all kinds of weather conditions, to say nothing of the vibration caused by gunfire at close quarters.

Such views (very fortunately for us) appear to have been accepted in those countries which were to become our enemies in the war. Some of them, at any rate, worked before the war broke out on radar; but they seem to have devoted comparatively little money or energy to developing a system which they could see no means of converting into a robust and practical weapon of attack or defence. All enemy countries developed some kinds of radar during the war, probably spurred on to do so by realising how successful it was in our hands. None of them produced apparatus approaching ours in accuracy or general efficiency.

In Great Britain the authorities were quick to grasp the possibilities of radar. This country is small, with its population and its centres of industry massed in certain areas. Even before 1939 it was within easy bombing range of Germany and therefore likely to suffer severely if forced into war with that country, which was boasting of the might of its immense air force. Clear-sighted people realised some years before war came that Germany was arming as fast as she could with but one end in view. There was no time for us, with the means of production that we then had, to build up a huge supply of fighter aeroplanes and anti-aircraft guns, or to train the men to operate them. Radar, if it could be made reliable, robust and simple to work, might be our salvation.

It was decided early in 1935 that work on radar should go forward and that no effort should be spared to make it a success. No effort *was* spared. Intensive work was done by a small band of brilliant men. Radar was a success and the fact that we had it in being when war came was our salvation.

Actually the first radar station not only in Britain but in the world was in operation in this country in the autumn of 1935. It could detect aeroplanes at 50 miles. By 1938 the range had been increased to 150 miles. More stations were then working and the building of a complete chain of them along our east and south-east coasts was under way. This chain was completed by the spring of 1939 and the rest of the coastline was equipped with radar soon after the outbreak of war. It was good; but it had one serious limitation: it could not detect low-flying aircraft. Special apparatus was designed for this particular purpose and a new chain of stations known as CHL (chain low-flying) was erected after the war had begun.

CHAPTER XIV

Radar in War

SO far, radar apparatus of all kinds has been classed under two main headings: instruments designed purely to detect targets at great distances and to locate them approximately and those whose purpose is to give accurate ranges and exact location of nearer targets. Both classes contain instruments of many kinds, each of which is designed for a particular purpose. The most modern methods actually make possible the accurate location of targets at great distances; even these are pin-pointed and not just approximately located. The useful applications of the radar principle in warfare are many and varied. Development went on unceasingly during the war and new apparatus for special duties was continually appearing.

Something has already been said of the principle of the absolute altimeter. Making use of ultra-short waves, it enables the pilot to whose aircraft it is fitted to measure at any time his height above the ground that is directly below him. The ordinary altimeter does not do this: it indicates the height of the aeroplane above sea-level, or above some fixed "zero" such as the level of the aerodrome from which it started. So long as he is on his course and has good maps the ordinary altimeter enables the pilot to make sure that his height is sufficient to clear any hills or mountains that he must cross. But if he loses his way and does not know his whereabouts on the map he can have no idea of what is ahead of him. There have in the past been terrible accidents due to pilots losing their way and flying into cliffs and mountain sides. By indicating the height above the ground over which he is actually flying the absolute altimeter may give warning that it is rising towards a mountain and so give the pilot time to avoid disaster by gaining height. But a far more useful instrument can be developed if centimetric waves are used; then, as we shall see in a moment, actual features of the ground below can be recognised from their shapes shown on the cathode-ray tube.

In the earlier part of the war, attacks by the R.A.F. on enemy centres of production were not infrequently rendered ineffective—or at any rate less effective than they should have been—by thick cloud or haze over the target. Targets might also be screened by man-made "bad weather" in the shape of smoke screens. Later on, you may remember cryptic announcements in the news bulletins to the effect that, though the target was obscured, an effective attack was made, bombing having been done by instruments.

An instrument largely concerned, whose official title is H_2S, was generally known as the magic box or "Gen" box. This is a small specialised radar set carried in the bomber. The way in which it got its rather strange looking name is interesting. When the idea was first submitted to one eminent authority he considered it for some time and was so little impressed by its possibilities that his comment was: "It stinks." It was, therefore, dubbed H_2S, the chemical symbol of sulphuretted hydrogen, one of the most malodorous of gases. H_2S may be described as something like a wireless version of the echo-sounding gear used by ships. We saw in Chapter III how the echo-sounding gear functions: as the ship steams along on the surface, pulses of sound waves are sent straight downwards, reflected back from the bottom and picked up by a delicate receiver. The depth at any point is determined by timing the return of the pulses; by the use of automatic recording apparatus a picture of the strip of sea-bed over which the ship sails may be obtained in much the same way as the inked trace on the drum of a recording barometer makes a record of climatic conditions.

The H_2S apparatus of an aeroplane also sends pulses downwards, but these are pulses of centimetric radio waves. Its record, made on the screen of a special kind of cathode-ray tube, is not a permanent one; it is a constantly changing picture showing the main features of the ground over which the aeroplane is flying. This cathode-ray tube is known as a PLAN POSITION INDICATOR or P.P.I. and as it is an important part of other centimetric radar systems as well as of H_2S, it may be well to devote a little time to seeing how it works.

In cathode-ray tubes of the kinds which we have discussed so far the time base, formed by the rapid movements of the spot, consists of a trace which appears as a stationary bright line lying across the middle of the screen. In the P.P.I. the spot starts its journey from the centre of the screen and moves outwards towards the edge of the screen; but the trace does not remain in one fixed position: it is made to revolve twenty times a minute or more. Fig. XIV. 1 will make this clear. If the first journey of the spot is *O-a*, the second is *O-b*, the third *O-c*, the fourth *O-d* and so on right round the circle of the screen.

The combined transmitting and receiving aerial of H_2S and its reflector forms the SCANNER. The scanner rotates and the time base of the P.P.I. tube revolves in exact synchronism with it. Thus when the scanner is pointing due ahead of the plane, the time base is at "12 o'clock"; it is at "six o'clock" when it points due astern, at "3 o'clock" when it points full to starboard, "9 o'clock" when it points full to port and so on. In aeroplane equipment this rotation of the aerial—and therefore of its lookout—did not become feasible until centimetric waves were used. For such waves the aerials are tiny. The half-wave dipole

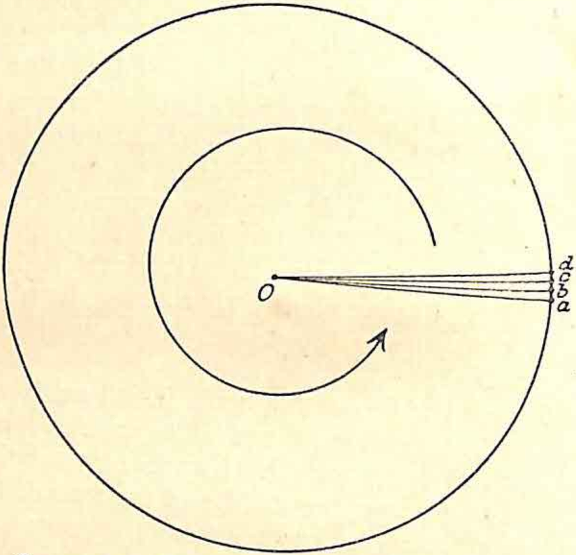


Fig. xiv. 1.—Illustrating the principles of the P.P.I. The spot moves outwards from the centre of the screen to the edge along *O-a*, flashes back to the centre and makes its next journey along *O-b*, *O-c*, *O-d*, etc. Thus the time base trace revolves and sweeps over the whole surface of the screen.

required for 10 centimetre transmission and reception is under two inches in overall length. When transmitting, the H_2S aerial sends down a narrow beam, invisibly illuminating at any instant a slice of the ground below, as shown in Fig. xiv. 2. The look-out when the aerial is receiving is of the same shape, so that it "sees" at any instant only the ground reached by the radiation from the scanner. As the scanner revolves, it sweeps over a large circle of ground below, the centre of the circle being normally the point vertically below the aeroplane.

Several substances fluoresce under the impact of a stream of electrons and can be used for making the screens of cathode-ray tubes. Some of them glow only for a brief instant, after the bombardment has ceased, but with others the brightness lasts for some time. Screens made of substances of the latter kind are said to have long AFTERGLOW and these are the kind that are used for P.P.Is.; when a break occurs and causes a bright spot on the screen the glow continues until the revolving time base comes round again and freshens it up. The surface of ordinary more or less level soil sends back echoes of moderate

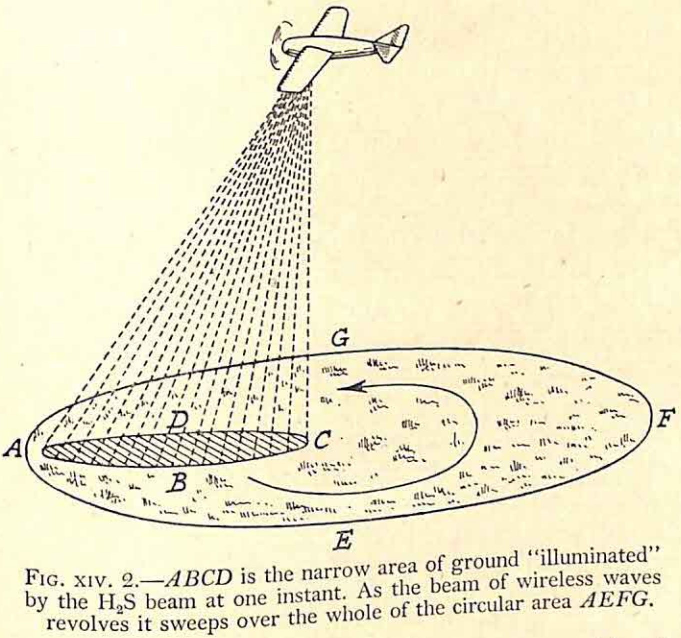


FIG. XIV. 2.—*ABCD* is the narrow area of ground "illuminated" by the H_2S beam at one instant. As the beam of wireless waves revolves it sweeps over the whole of the circular area *AEFG*.

strength, so that when an aeroplane is passing over it the screen of its P.P.I. glows faintly all over; but outstanding features, such as buildings, return much stronger echoes and give rise to brighter patches on the screen. No echoes come back from water, which therefore shows up black on the P.P.I. screen.

A little thought will show that since the spot normally starts from the centre of the screen, this point represents zero range, or the position of the aeroplane itself. The farther away is any feature from which strong echoes are returned, the farther from the centre will be the breaks caused by these echoes. Circles at various distances from the centre may be inscribed on the screen to show the pilot how far he is from the objects indicated by the breaks. A graduated scale drawn round the edge of the tube also enables him to measure the direction in which they lie, for the revolving time base always indicates that in which the receiving aerial is looking out when the breaks on the trace occur.

The shapes of towns are painted in remarkably clearly by the mass of breaks that they cause on the revolving time base, so clearly in fact that they can be recognised by comparing them with the shapes on a large-scale map. Bombing can therefore be done with the certainty of excellent results, no matter what the state of the light or the weather, by an aeroplane fitted with the H_2S. Plate I shows the picture of land and water below him that is "painted" on the navigator's P.P.I. tube. The H_2S picture of Plate I should be compared carefully with the circled area of the accompanying map. H_2S has another sterling quality: it is not deceived by camouflage. The Germans went in for camouflage whole-heartedly, even going so far as to cover up lakes and rivers with floating disguises and to construct dummy towns realistic enough to deceive the human eye. But the flimsy counterparts of the genuine target by camouflage experts do not deceive the eye of H_2S; to it planks and garnished netting bear no resemblance whatever to the bricks and mortar or the reinforced concrete of the real target.

Other applications of radar made heavier raids and still more accurate bombing possible in any kind of weather that would allow taking off and landing to be done. One of these, known as "Gee" enables a bomber to obtain its exact position at any time. It was due to the adoption of this system that the number of bombers that could be massed against one objective on a single night was increased from 100, the previous maximum, to 1,000. "Oboe" is a marvellous device which enables a 'plane to be guided from a ground control station hundreds of miles away to within a few yards of any desired position. During the later raids on German industry our pathfinding aeroplanes were navigated by means of "Gee" to a selected area close to the target. Then "Oboe" took over, directing them to the exact spot. The signal to release their bombs was given by controllers in this country, who, by means of "Oboe", knew the position of the bombers exactly. "Rebecca-Eureka" was a system specially devised for glider and parachute landings. An advance party of airborne troops and one part or the apparatus, "Eureka," were dropped by parachute. "Eureka," which may be described as a radar beacon, responds automatically to signals reaching it from "Rebecca," carried in succeeding aircraft, and guides them to the proper landing point. Airborne troops could thus be concentrated unfailingly in a small selected area.

When raids by enemy bombers in the hours of darkness began, the night-fighter pilot had as dangerous and as difficult a task as can be imagined. He had to take off and land in the dark, using a flare-path which gave very little aid for his return if fog came down, as often it did, after he had been flying for some time—"Fido,"* remember, had not then been invented. The controller on the ground could and did tell him by wireless telephone what course to fly in order to close an enemy bomber. But to engage such a bomber successfully he had to reach a position from which he could see it, and you may imagine how difficult it was to do that on a pitch dark night. If his course was only a comparatively small number of feet too high or too low, he might pass quite near to his quarry without ever getting a glimpse of it. Then, though he might not see the hostile bomber, one of its gunners might see him and open fire with deadly effect.

Small wonder, then, that in those days casualties amongst night-fighter pilots were heavy and that the toll that these brave men took of hostile raiders was not large. But those responsible for the defence of Great Britain were not sitting still. It was realised by them that radar could be so developed as to play an important part in the defence of the country by night fighters. Research and development work went forward vigorously and early in 1944 the toll of raiders taken by the night-fighters had reached such proportions that the enemy realised that the game was no longer worth the candle. Night raids by his bombers dwindled in magnitude and frequency and finally ceased altogether. The Luftwaffe could not face the heavy losses which our radar made it certain that he would sustain if he staged any kind of bombing raid under what had once been the cover of darkness.

Before the form of radar specially designed to aid the night-fighter pilots had been developed, every effort was made to increase their standard of vision in the dark. They were selected for the work after special eye tests. I well remember seeing on the dining tables of R.A.F. messes to which night-fighter pilots were attached small bowls of semi-transparent pellets about the size of peas. Inquiry elicited that these contained halibut liver oil, which is rich in a vitamin that makes the eyes more sensitive in a poor light. But for all these efforts and for all the gallantry and skill of the night-fighter pilots enemy bomber crews still regarded the risks of raids made in the darkness so lightly that those using French and Belgian aerodromes were overjoyed to have the chance of making two or even three trips to this country in a single night, since each crossing of our coast earned them a spell of leave. Very different was the state of affairs sometime later when our night fighters were guided to their targets by the eye of radar, which is as keen and as clear in darkness as it is by daylight. By that time enemy bomber crews knew that if they ventured over this country they had a much greater chance of figuring in the casualty lists than in the leave rotas.

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* The method devised for dispersing fog over aerodrome runways by great systems of oil burners.

What made our skies so unsafe for enemy raiders was a combination of two specialised types of radar. One of these (G.C.I.—ground control of interception), situated on the ground, scanned the entire dome of sky above it and showed on the screen of a large P.P.I. tube a kind of sky map containing all aircraft, hostile or friendly, that were flying within a radius of many miles. Aided by this, the control officer on the ground could direct the night-fighter pilot by wireless telephone to steer the course that would bring him close to his quarry. On the screen the fighter could be seen approaching the raider. Then, when the distance between the two was comparatively small, the night-fighter pilot brought the radar set fitted to his aircraft into play. This system was known as A.I. (aircraft interception). The raider appeared on its cathode-ray tube as a spot of light and the navigator of a night-fighter had only to direct the pilot to manipulate his flying controls until the spot was in the centre of the screen to be sure that their craft was making straight for its prey. The earlier forms of A.I. operated on the ultra-short waves. They were good so far as they went, but they had nothing like the accuracy and the clear definition of the types using centimetric wavelengths which were developed later.

In the early days of the war searchlight detachments had nothing to help them in the difficult task of spotting their target and directing the projector towards it but instruments which operated by means of sound waves picked up from the target. The help that these gave was so inadequate that high, fast-flying targets were comparatively seldom illuminated. Most readers must have seen searchlight beams before 1942 groping about the sky in search of their targets and many will have realised how restricted is their look-out since the light is focused into so narrow a "pencil."

S.L.C. ("Elsie") is a system of radar specially designed as a searchlight aid. The letters stand for searchlight control. The broad principle is that the section of the sky in which the target is known to be from information received from radar tracking stations, is scanned by invisible revolving wireless beams giving a much wider look-out than that of the searchlight. Actually, the system switches the look-outs of four separate aerials above, below, right and left of the target in the way outlined on page 118. Once "Elsie" has spotted the target, the searchlight is directed on to it before being switched on. When the order to expose is given the target is seen nine times out of ten at or near the centre of the beam of light.

The Navy, too, made great use of radar, which enabled it to take full advantage of the enormous ranges of modern big guns, ranges which even in daylight are beyond those of the eye, owing to the curvature of the earth and the waters upon its surface. An early success of very great importance achieved with the help of radar was the victory off Cape Matapan by the Mediterranean Fleet. The action took place on a pitch dark night at ranges so long that the Italian fleet had at first no idea that any of our ships were in the vicinity. Out of the darkness came shells of the largest calibre, directed with deadly accuracy. The Italian fleet was scattered and many of its ships sunk almost before it had realised what was happening to it.

Another naval feat for which credit must go to radar was the pounding of the *Scharnhorst* by our heavy guns long before she was in sight. She was so damaged that she could not escape her fate when the range was closed.

Other types of Navy radar apparatus were designed for many special purposes. Amongst them may be mentioned A.S.V. (aircraft to surface vessel), the anti-submarine equipment which detected enemy submarines when they came to the surface, as all submarines must from time to time for ventilation and battery recharging. A.S.V. was also used in Coastal Command and R.N.A.S. aeroplanes, guiding them unfailingly to any surfaced U-boat. It was one of the most successful factors in the long battle against hostile submarines; even Admiral Doenitz had to admit that the failure of his U-boats to carry out their programme of starving Britain into submission was mainly due to the superiority of what he called our "technical equipment."

Some of the work done by radar for the Army has already been mentioned. The part which it played in the destruction of V1 flying bombs before they could reach their objectives is not perhaps fully realised. They were detected by its unfailing eye very soon after they had been launched. Their courses were plotted and it was thus possible to give the guns both timely warning of their coming and data which enabled them to be engaged successfully. When the enemy first began to send them over the guns had to be re-deployed and an entirely new technique worked out. In those early days of the V1 attack it was not surprising that considerable numbers of the flying bombs penetrated our defences and reached their marks. But later radar and gunnery methods were devised which took a heavy toll of them. Almost 98 per cent. of the V1s that came within range of the guns after that were shot down by A.A. artillery before they could do any harm. As one A.A. Battery Commander put it to me: "When the doodle-bugs first started coming over the Brass Hats told you what a fine fellow you were if you managed to shoot one down. Before the end they wanted to know the reason why, if you let one get away." But for radar the damage and loss of life due to the V1s would certainly have been many times as great as it was.

One of the most remarkable radar devices of the war was largely responsible for the success of the guns against the V1 flying bombs. This was the Radio Proximity Fuze. The A.A. gunners' problem is not confined to predicting the future position of his target and laying his guns so that shells and target will reach it at the same moment. The shells must be made to burst, and to be effective those bursts must occur within a few feet of the target. During the greater part of the war time fuzes were in use. These contain a mechanism which is set so as to detonate the shell at a given time after it has left the gun. As a fast-travelling shell must burst very close to its target in order to be sure of destroying it, a minute fraction of a second in the timing makes all the difference between a burst that is lethal and one that is harmless.

No methods of prediction and no timing mechanism in the fuze can be sufficiently exact to ensure the bursting at precisely the right instant of more than a very small percentage of the shells fired, for a shell may pass within a yard of its target and yet do it no damage if the burst does not occur till it has travelled a short distance further.

The Radio Proximity Fuze contains a miniature radar receiver and transmitter. The pulses sent out by the transmitter return as echoes to the receiver and by a most ingenious arrangement the receiver operates a detonating device at exactly the right instant. Provided that the gunner has played his part and, with the aid of the predictor, made the shells arrive near the target, the Radio Proximity Fuze does the rest.

Had we had this fuze during the blitz raids, it is likely that few enemy bombers would have got through. The idea was originated in 1940, but, as may be imagined, a long time was needed in order to give it practical form. We had not the research personnel available and the idea was handed to our American allies, who produced the Radio Proximity Fuze just in time to deal with the V1 attacks.

You may have wondered how A.A. gunners and those of the Navy can make sure whether an aeroplane or a ship that they cannot see is hostile before they open fire upon it. All aircraft, enemy or friendly alike, appear on the cathode ray tubes of radar receivers as "breaks" shaped like inverted Vs, or as spots of light. How, then, can the break produced by an echo from an enemy bomber be distinguished from the exactly similar break due to one of our own aeroplanes? This is done by a device known as I.F.F. (identification: friend or foe). When a radar pulse reaches a friendly aeroplane it causes an instrument installed in it automatically to transmit a recognition signal which is seen on the cathode-ray tube close to the break. Targets whose breaks are not accompanied by the signal are shown up as hostile.

Radar has its tragedies as well as its successes. You may remember the report on the Pearl Harbour disaster, when Japanese aeroplanes disabled a large part of the American Pacific Fleet whilst their diplomatic representatives were engaged in "friendly" discussions at Washington. The report issued at the time by the U.S.A. authorities and printed in our newspapers stated that some considerable time before the arrival of the Japanese bombers the N.C.O. in charge of the radar equipment reported to his officer that a large formation of aeroplanes, then over a hundred miles away, was approaching. The officer decided—there had, you may recall, been no declaration of war—that these must be some expected American aircraft. Warning of that treacherous attack was given by radar; but, as was perhaps not unnatural in the circumstances, it passed unheeded.

CHAPTER XV

Radar in Peace

THOUGH warfare is rightly detested by civilised nations on account of the suffering and the destruction that it must bring, it would be far from true to maintain that there have not been many discoveries and developments of the greatest benefit to mankind which were the direct result of wars. When a country is fighting for its very existence it must exploit every available means within reason of making the sea, the land and the air as dangerous as possible for its enemies and as safe as possible for its own citizens; for only in this way can it hope to survive. When a promising field of research is found, scientific investigation, elaborate tests and eventually manufacture on a large scale must go forward without regard to the monetary cost. Time becomes of inestimable value: the sooner an idea can be given practical form the greater will be the relief to friends and the injury to foes. Brains and energy are therefore concentrated upon it in a way that is scarcely possible in peacetime; and time and again development work under the stimulus of war leads to successes in a number of months that might have been years or tens of years under normal conditions.

Wireless telephony was, for instance, in a more or less elementary state in 1914. Such was the progress made to meet the demands of warfare that when peace came the stage was set for the early appearance of broadcasting, which has since became so much a part of everyday life.

Intensive work during that war resulted in enormous advances in medical science, of which plastic surgery and the virtual conquest of typhoid fever are outstanding examples. In aeronautics and in automobile engineering progress was rapid and remarkable.

During the great war that has recently been brought to a victorious end still more wonderful advances were made, many of which in years to come will contribute to man's happiness, comfort and safety. The atomic bomb is by far the most terrible weapon ever devised; but owing to the intensive work done by some of the finest brains in Britain, Canada and the United States in perfecting this engine of destruction there is little doubt that we shall have available for industry and certain transport services at no very distant date a source of power vastly greater than any that we now have. In 1939 those scientists who believed that one day it might be possible to harness atomic energy for the service of man mostly held that half a century of work and the expenditure of huge sums of money would be needed before success could be achieved. Owing to the needs of war no less than £500,000,000 was spent by the allies on research and development in this field, a company of brilliant men such as has never before been assembled was assigned to this one problem and, in the words of Mr. Churchill, the work of fifty years was done in five. Before the war the use of atomic energy to serve man's needs was little more than a dream. That dream has now been fulfilled in one respect: atomic energy has been used as a destroyer; soon it may be the greatest aid to construction that we have ever had.

Radar has been instrumental in the war in bringing down or sinking innumerable enemy aeroplanes and ships. It was developed purely as a weapon of war; but in peace it will have a larger and larger part to play in making travel safer by preventing the very things that it was designed to bring about in war. There was no period of waiting for radar to begin its peacetime good services once the war was over. Many of the radar aids to navigation by sea and air required no alteration to adapt them for civilian use; all who have travelled by ship or airliner since peace returned have had, though possibly they may not have realised it, the benefits of one or more kinds of radar to make their journeys safer.

H_2S is one of these; and, just as the centimetric H_2S was a vast improvement on the ultra-short wave absolute altimeter, so we may expect in the future a far better form of panoramic radar. The present instrument is able to paint in the rather blurred shapes of conspicuous features of the ground below because its centimetric wavelength gives far higher definition than could be obtained on waves whose length is measured in metres. The panoramic radar of the future may well use millimetric wavelengths (a millimetre is about a twenty-fifth of an inch) and paint on its cathode-ray tube pictures so clear that the pilot will be able to see what is below him almost as well in darkness or cloud or fog as in bright daylight. To-day the picture is comparable with the earliest efforts of television; to-morrow it may provide the pilot with the clear views of radar television.

Once a means of making high-power transmissions on these minute waves has been found, radar television will develop in other interesting ways. At present ships, aeroplanes and other targets appear on the screen of the cathode-ray tube simply as inverted-V breaks. It seems likely that the radar operator of days to come will do more than locate his target; he may see its actual shape on his cathode-ray tube and may thus be able to identify it. The harnessing of the waves measured in millimetres is certain to come; but there is no need to look ahead to that day to realise how valuable radar in its present form is to humanity.

How often has one read the harrowing stories of survivors of a shipwreck adrift in an open boat for days or even weeks. Their hopes are raised by the sight of a distant ship or of an aeroplane; but neither ship nor aircraft sees them . . . The search for victims of a shipwreck or of an accident to an airliner in mid-ocean will no longer be the difficult and chancy business that it once was, for A.S.V. has other uses besides the detection of surfaced enemy submarines. It was used in the war for finding airmen who had been forced down into the sea and it proved to be so sensitive that is could detect at a great distance a tiny rubber dinghy containing two men.

Radar has already become the greatest of all navigational aids to ships at sea. Fog and falling snow used to be the nightmares of ships' officers in narrow waters or in sea-lanes where there is much shipping. In such conditions the keenest human eye may be able to see only a few yards in any direction. In fog, too, the ears are no longer safe guides to the direction from which a sound is coming and the siren of another ship may seem to be sending its warning note now from one point of the compass and now from another. Radar apparatus is entirely unaffected by such conditions. It gives infallible indications to the ship provided with it of the exact positions, courses and speeds of other unseen vessels. And there are other dangers, such as icebergs or drifting derelicts that the radar look-out spots and locates, always giving ample warning of their presence. Besides reducing the risk of collision with icebergs, other vessels or floating wreckage to a minimum, radar makes easier the navigation of unfamiliar or poorly charted waters and lessens the dangers of unlighted coasts. Radar will be blessed by the deep-sea fisherman in thick weather. His own small vessel—trawler, drifter or smack—may not have the apparatus; but he knows that he no longer risks being run down by larger ships, in which the eye or radar is keeping untiring watch.

Ships large and small can find their exact positions at any time so long as they are within range of shore radar stations. In foul weather, when it is impossible to use the sextant or the sun or a star, they have no longer to rely on dead reckoning. In answer to a wireless call radar gives them their position more accurately than it could be determined by the expert use of fine navigational instruments. Certain types of radar equipment actually locate the position of an object more precisely than it can be shown on any but the largest scale map. Marine radar is dealt with at length in the next chapter.

Already an international body (P.I.C.A.O.) has made recommendations that radar approach and blind landing systems should be standardised at aerodromes the world over which are used by commercial aircraft carrying passengers or freight. There are many rival systems for navigation and for blind landing at present, and agreement has not yet been reached as regards which shall be adopted. Rather than lose time our own authorities have installed Loran as a navigational control and G.C.A. (ground control of approach) for landings. Both are systems of American origin and are widely used in the U.S.A.

Loran (the name is a contraction of long range radar navigation) is very similar to Gee, except that it uses longer wavelengths. G.C.A., also known as "Talk-you-down," is a system which enables the control officer to see on his instruments the exact position and height at any instant of the aircraft whose landing he is handling. He gives a constant stream of directions to the pilot by radio telephone; in fact he talks the pilot down. The great advantage of G.C.A. is that no instruments save a radio telephone need be carried in the aircraft. Its greatest drawback is the language difficulty, for it becomes of no use if a foreign pilot cannot understand exactly the directions given to him.

Another navigation system now available both to aircraft and to shipping in and around this country is Decca. So long as a 'plane or a ship carries the necessary receiving instruments it can ascertain its exact position at any moment. To the chains of Decca stations now operating in this country and on the Continent of Europe others are soon to be added. Gee, Loran and Decca are more fully discussed in Chapter XVI.

Scientists are already considering the possibility of radiolocating the moon and so of determining its exact distance from the earth beyond any possible doubt. There seems no reason why this should not eventually be accomplished; successful experiments have, in fact, already been made. The moon should provide excellent echoes, if means of transmitting suitable pulses can be evolved. Her average distance from us is, in round figures, 240,000 miles, and the echo would return in a little over 2½ seconds. Possibly the process may in time be extended to some of the planets. The out-and-home journeys of the wireless waves would be accomplished in reasonably short times in the case of our nearer neighbours in space, Mercury, Venus and Mars; and even from so distant a planet as Uranus the echoes would come back in about five hours. But it seems unlikely that, whatever progress is made in radar technique, man will ever be able to measure the distances of stars in this way, for echoes from the nearest known star would not return for more than 8½ years and for most stars the double journey would need hundreds or even thousands of years.

Radar may certainly be classed as the outstanding contribution of science to the most highly technical of all wars. The atomic bomb, represents, perhaps, a greater achievement from the purely scientific point of view; but we should have won the war without it, though it would have taken longer to do so and thousands more of our sailors, soldiers and airmen would have lost their lives before victory came. Without radar we could not have won, for we could never have stood alone against the enemies who in 1940 were believed by almost the whole world except Britain and the Empire to be about to overwhelm us.

The wartime story of radar was indeed a wonderful one. Its peacetime story has yet to be unfolded, but no one can doubt that it will be more wonderful still.

CHAPTER XVI

Marine Radar

THREE different kinds of radar are used to help ships to find their way at sea or in narrow waters at times when the human eye can see little or nothing. The three systems are:

(1) Shore-based navigational radar,
(2) Harbour radar,
(3) Shipborne navigational radar.

All systems of the first kind of sea radar work on the same basic principle and all can be used as navigational aids by both 'planes and ships. Gee was the first system of this kind to be evolved and all others are descended from it. The name Gee, by the way, is simply the initial letter of "grid," for this kind of radar provides, as we shall see, an invisible grid or lattice of guiding lines "drawn" by radio waves. Hold a small stone in either hand and, with the arms stretched widely apart, drop them simultaneously on to the calm surface of a pond. The ripples travel outwards in circles and the two sets of rings give rise to what is known as an interference pattern, as shown in Fig. XVI. 1. You will see that the pattern forms a lattice on the surface of the water, dividing it up into a number of small, distinct areas. Shore-based, navigational radar operates on similar lines, though curves of a different sort are used. The "stones" are radio pulses, sent out simultaneously or at a fixed time-interval by transmitting stations; the lattice is produced by the electro-magnetic waves which radiate outwards from the transmitters.

Suppose that there are two transmitters situated 100 miles apart, as in Fig. XVI. 2 (*a*). One of these, *A*, is the master station and is adjusted to send out, say, 500 short pulses every second. *B* is the slave station, which can do nothing on its own, but must obey instantly every order given by *A*. Each one of the pulses radiated by *A* delivers an order to *B* to transmit a pulse. *A* cannot make *B* send out pulses simultaneous with its own, for the order has to travel to *B* and that journey must take time. The highest possible speed in the universe is that of electro-magnetic waves, which, travelling at 186,200,000 miles in a second, cover in round figures one mile in 5 microseconds. Remember that we are thinking now not of the out-and-home time of a radar pulse and its reflected echo, but just of the outward travel of radio waves.

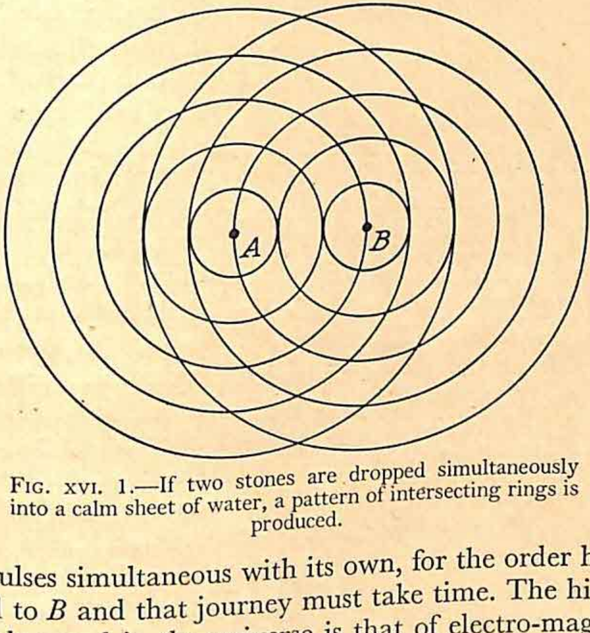

FIG. XVI. 1.—If two stones are dropped simultaneously into a calm sheet of water, a pattern of intersecting rings is produced.

Since *B* is 100 miles from *A*, the order pulse takes 100 × 5, or 500 microseconds to arrive. The pulse triggers

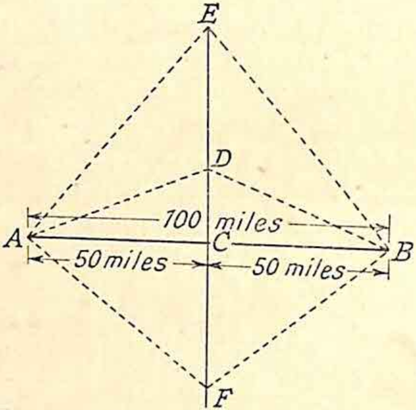

FIG. XVI. 2 (*a*).—*A* is the "master" transmitter and *B* the "slave." Every pulse sent out by *A* causes an "order" to be given to *B*, which obeys by sending out a pulse exactly 1,000 microseconds after *A*'s. If the *B* pulse is received by a vessel just 1,000 microseconds after the *A* pulse, the two must have travelled to the vessel by paths of equal lengths. The navigator then knows that he is *somewhere* on the straight line *EF*, since any point equally distant from *A* and *B* must be on this line. *EF* passes through *C* the mid-point between *A* and *B* and is at right angles to the straight line *AB*.

off *B*. Various small delays occur in *B*'s response to the order from *A*: the triggering device needs a little time to grasp the order and to function; there is a minute delay between the triggering and the actual emission by *B* of a pulse. To allow for every eventuality we may so adjust *B* that the pulse goes out exactly 1,000 microseconds after the despatch of the order by *A*. This gives *B* the colloquial oceans of time in which to obey. Even so, *B* is no sluggard. The most exacting of regimental sergeant majors could hardly accuse men of not jumping to it if his orders were carried out within one-thousandth of a second of his giving them!

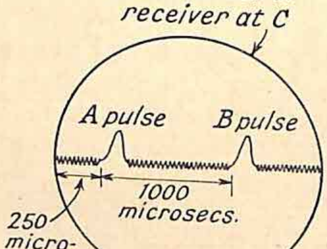

FIG. XVI. 2 (*b*).—What the C.R.T. shows if you are at the point *C*.

Now suppose that you are at *C* in Fig. XVI. 2 (*a*), that is at a point just half-way between *A* and *B*, and that you have a receiver equipped with a C.R.T. stopwatch. A pulse from *A*, 50 miles away, reaches you 50 × 5 = 250 microseconds after it leaves *A* and causes a break to appear in the corresponding position on the C.R.T. trace (Fig. XVI. 2 (*b*)). The *B* pulse, despatched 1,000 microseconds after the despatch of the *A* pulse, also has 50 miles to travel before reaching the receiver. Hence it arrives 1,000 plus 250 = 1,250 microseconds after the *A* pulse was despatched and 1,000 microseconds after the *A* pulse was received by you. A second break on the C.R.T. trace occurs at a position corresponding to the passing of 1,000 microseconds since the arrival of the *A* pulse.

So long as the two breaks are 1,000 microseconds apart you must be at *C*, or at some other point equally distant from *A* and *B*. Any such point can lie only in some position on the straight line *EF*, which bisects the baseline *AB* at right angles. If, then, the *B* pulse comes in 1,000 microseconds later than the *A*, you know that you are *somewhere* on the straight line *EF*.

Next move to *G* in Fig. XVI. 3, where you are 60 miles from *A* and 40 miles from *B*. The *A* pulse now reaches you 60 × 5 = 300 microseconds after it is sent out; the *B* pulse comes in 1,000 plus 40 × 5 = 1,200 microseconds after the despatch of the pulse from *A*. The delay between the arrivals of the *A* and *B* pulses is now only 1,200 − 300, or 900 microseconds.

When this delay is recorded on the timebase you must be at a point at which the path from *B* to your aerial is 20 miles shorter than the path from *A*. If you care to plot the positions of points lying 70 miles from *A* and 50 from *B*, 80 miles from *A* and 60 from *B*, 90 miles from *A* and 70 miles from *B* and so on, you will find that these points lie not on a straight line, but on a curve. Thus, if the *B* pulse comes in only 900 microseconds after the *A* pulse, you must be *somewhere* on the curve *HI*. A curve, in which any

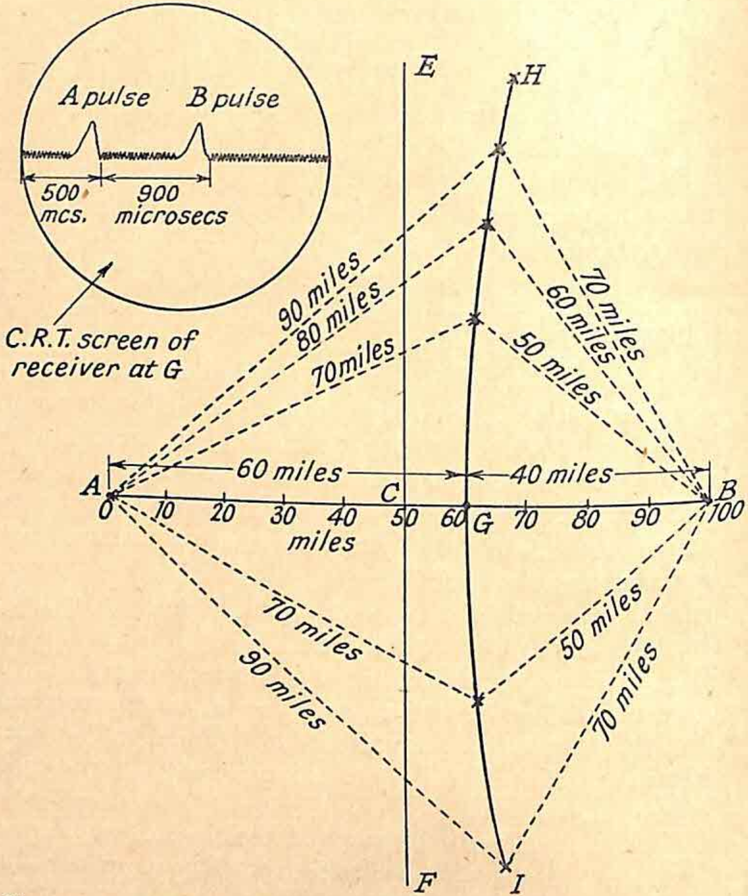

Fig. xvi. 3.—If the *B* pulse comes in only 900 microseconds after the *A* pulse, the path of the *B* pulse must be 20 miles longer than that of the *A* pulse. The navigator now knows that he is at *G*, or at some other point on the curve *HI*.

point has always the same unchanging difference in range from two fixed points outside it is called a hyperbola.

Points equidistant from *A* and *B* lie *somewhere* on the straight line in the middle of Fig. XVI. 4, which is marked 1,000 to indicate that the time delay between the arrival of the *A* and *B* pulses is 1,000 microseconds. All other points must lie *somewhere* on hyperbolas. The curves shown in the drawing are those for time differences from 600 to 1,400 microseconds. They are drawn at 100 microsecond differences, or 10-mile intervals. You will realise that curves at very much smaller intervals can easily be drawn. They are in fact drawn on hyperbolic radar navigation charts.

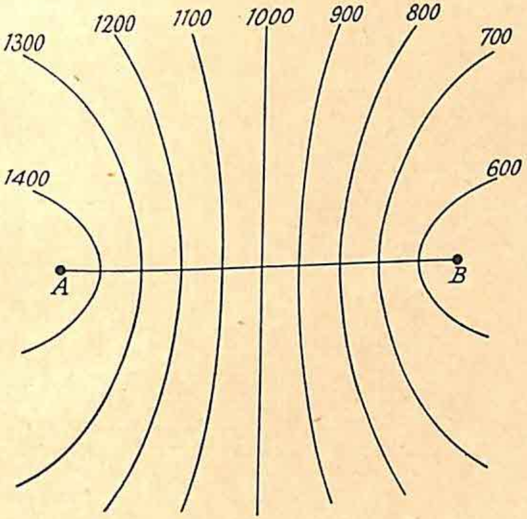

FIG. XVI. 4.—A family of curves for the same pair of stations. The figures indicate the interval in microseconds between the arrival of the *A* pulse and that of the *B* pulse.

Clearly it is not enough for a navigator to know that he is *somewhere* on a straight line or a curve drawn on his chart; he must know the exact point that he has reached. This information can be given to him by a chain of radar stations consisting of a master and two slaves, as shown in Fig. XVI. 5. Imagine that his receiver now displays two pairs of pulses, one pair indicating the delay between the *A* and *B* pulses and the other the delay between the *A* and *C* pulses. No. 1 pair gives indications which show that he is *somewhere* on the curve *OP;* from pair No. 2 he finds that he is *somewhere* on the curve *QR*. There are two points which lie on both *OP* and *QR*. In a way which cannot be explained here the instrument indicates the right one and shows that his position is at *X*.

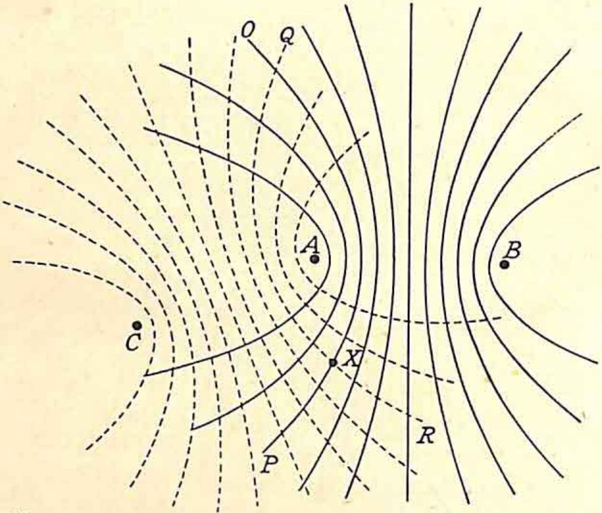

FIG. XVI. 5.—Radar lattice from a master station *A* and two slaves *B* and *C*. The *A–B* curves are shown by solid lines and the *A–C* curves by broken lines. In practice each set of curves is printed in its own distinctive colour on the chart.

Navigational radar on the hyperbolic system has been made both very simple and very accurate nowadays. It has been found best to use chains of four transmitters, consisting of a master and three slaves. There are thus three sets of curves, which are printed in red, purple and green respectively to form a fine lattice on the radar chart. The navigator does not watch a cathode-ray tube. Instead, he now sees on a small dial the identification numbers and the colours of the curves on which his position is at the moment. By referring to his chart bearing the red, purple and green lattices, he can pin-point his position instantly.

Gee, Loran and Decca are typical hyperbolic systems used by aircraft and ships. Gee and Loran both employ pulses, the former operating on very short radio waves and the latter on much longer waves. The Decca system does not use pulses at all. It operates on very long wavelengths and makes use of the difference in phase (pages 110–112) of waves arriving at the receiver by paths of different lengths.

Strictly speaking, none of these systems can claim to be true radar, for none of them uses the reflection of echoes by a target. They employ, though, a great deal of the technique of genuine radar, for all depend ultimately on the accurate measurement of minute time differences in the arrival of pulses (or wave-crests); it has, too, become customary to class them as radar and it is convenient to do so.

The second and third kinds of marine radar are both undoubtedly the genuine article, for each makes full use of transmitted pulses and of the echoes due to them. Both can probably trace their descent directly from A.S.V. and H_2S.

You will remember that in H_2S a rotating aerial, or scanner, causes a narrow beam or radiation to make a circular sweep. The scanner is synchronised with the radial timebase of a P.P.I. tube. Any echo returning from a target thus causes a break, in the form of a small luminous patch, to appear on the screen, at a position which indicates both the range and the bearing of the target. The range is shown by the distance of the break from the centre of the screen; the bearing can be read, with the aid of a fine cursor, pivoted at the centre, from a scale of 0°-360° of angle surrounding the circumference of the screen.

In both harbour radar and shipborne radar the P.P.I. tube screen shows a clear picture of the sea and all that is on its surface, as well as of coastlines, if any, within the range in use.

A good example of modern harbour radar is that installed at Liverpool. The estuary of the Mersey has long been notorious for its navigational difficulties at times when weather conditions make visibility poor. A long, narrow channel leads from Liverpool Bay to one of Britain's busiest ports. In misty weather the captain of a ship inward or outward bound must make the difficult decision whether or not to negotiate this channel. Once he has set out, either upstream or downstream, he must go on. The channel is too narrow to allow him either to anchor or to turn round, should conditions worsen. The man who has to make such a decision is not to be envied. Every tide lost by an overcautious captain means a cost to his owners in harbour dues, wages, food and so on, that may run to many hundreds of pounds. On the other hand, a master too willing to take risks might incur the blame for much heavier losses should an accident occur to his ship.

The Liverpool Harbour Radar, situated near the seaward end of the Gladstone Dock, does not control the movement of ships in the Mersey. That is, those who operate it do not issue orders to ships. It does, however, provide the harbour authorities with a complete picture, no matter what the weather, of the shipping in Liverpool Bay, and in the Mersey Channel. The master of any vessel lying in the docks or waiting in the Bay can obtain from the radar station at any moment by wireless a report on the shipping actually in the channel. If he decides to make the inward or outward passage, the pilot who directs the ship comes aboard with a portable radio set, tuned to the wavelength on which the operators of the harbour radar set send out a stream of information. In foggy weather pilot and captain can receive accurate information of the position of their own ship and of other vessels.

In the Liverpool Harbour installation, besides a small-scale image of the whole area shown on one screen, an ingenious arrangement divides the radar picture of the whole 14-mile channel into four sections, each on a separate screen. The sections have a slight overlap. The scale of this display is two inches to the nautical mile. In addition, there is a sixth screen devoted to what is termed a wandering display. This can be moved over any part of Liverpool Bay or the Mersey Channel by the operator. It can bring into radar view parts of the Bay not seen on the fixed screens; or it may be adjusted instantly to replace any of the fixed screens should one of these go out of action.

In shipborne radar equipment the scanner is usually mounted on a special mast or tripod. The beam sweeps right round the ship about 20 times a minute. When the beam is pointing straight ahead an extra-positive voltage is applied to the grid of the C.R.T., with the result that a thin bright line (Fig. XVI. 6) known as the heading line, appears on the screen. In the drawing the heading line is shown at 0° on the bearing scale. This is where it does appear when the switch controlling it is turned to "Relative Position." The bearings of targets are then read off as so many degrees from the ship's course. But if this switch is turned to "Stabilised Position," there is a different state of affairs. The vessel's gyro compass is made to take charge of the radar presentation; zero on the bearing scale now represents true north, the heading line shows the ship's course with reference to true north and the bearings of all

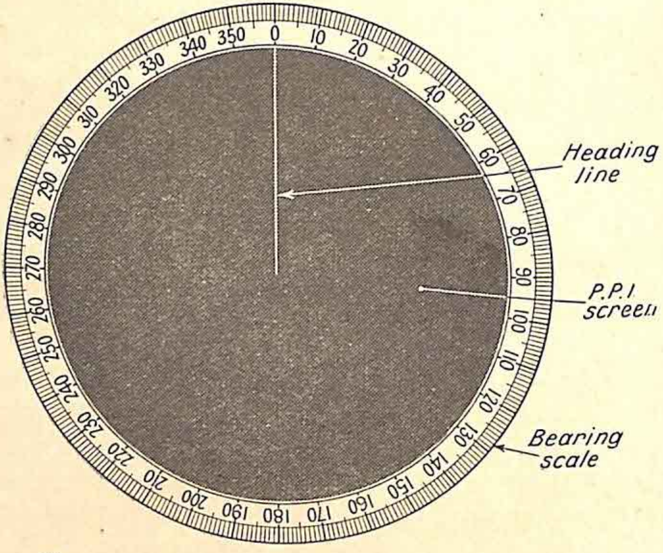

FIG. XVI. 6.—P.P.I. tube screen of typical shipborne radar.

targets have the same reference. We shall see in a moment how useful the stabilised position can be to the navigator in certain circumstances.

Bearings are read by means of a thin wire cursor, pivoted to the centre of the perspex or glass shield covering the P.P.I. tube and rotated by the movement of a knob. Ranges can be measured accurately by means of a device known as the range-marker. This is a thin luminous ring brought into being by turning a switch. A knob enables the diameter of the ring to be continuously increased or decreased. To measure a range the knob is turned until the range-marker ring just touches the edge of it nearest the centre of the screen. The ring is formed by putting a bright "pip" (positive voltage on the grid again) on to each run of the rotating timebase. The knob which controls the distance from the start of the timebase at which these "pips" occur is also geared to a mechanism which may cause figures to appear, like those of the mileage recorder of a speedometer, on the range indicator. Ranges are thus read off from a row of clear and unmistakable black and white figures.

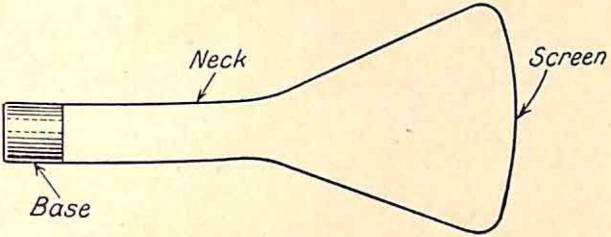

Fig. xvi. 7.—The shape of the magnetically controlled c.r.t. used as a P.P.I. tube and in television receivers. The cathode, grid and anode are inside the glass neck of the tube. The deflecting magnets are mounted outside the glass.

Before we go further it may be as well to clear up one point which you may have found puzzling: How is the timebase of the P.P.I. tube made to rotate round the centre of the screen? In the kind of c.r.t. which is used as a P.P.I. tube (as well as that in most television receivers) the beam of electrons which produces the spot is deflected not by means of plates and an electric field, but by means of magnets and a magnetic field. Fig. xvi. 7 shows the general shape of such a tube, as seen in profile. Inside the neck are the cathode, grid and anode, which form the electron gun. The coils which form the deflecting electromagnets are suitably shaped to fit round the outside of the neck. In television tubes these magnets are fixed and the timebase trace starts from the left-hand edge of the screen. The trace in P.P.I. tubes starts from the centre and, since the magnet coils (and therefore the magnetic field) revolve, the trace is in the form of a "spoke," rotating round the centre of the screen.

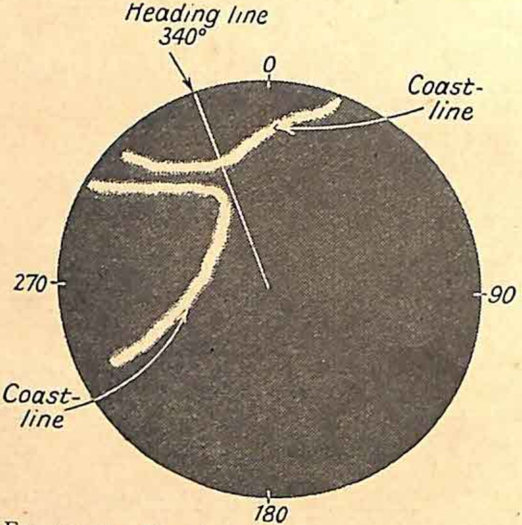

FIG. XVI. 8.—The picture seen as a ship approaches the mouth of a strait. Stabilised position and the 15-mile range scale are in use.

The magnets are locked to the scanner by means of a device known as the Selsyn (short for self-synchronising) transmission. The selsyn transmitter is driven by the shaft which turns the scanner; the selsyn receiver drives the magnet coils of the P.P.I. tube through toothed gear wheels. As the name selsyn suggests, the receiver and transmitter automatically keep step with one another; hence the position of the trace on the P.P.I. screen corresponds at every instant exactly with the position of the beam of waves radiated by the scanner in its sweep round the horizon.

Fig. XVI, 8 shows the kind of picture that the navigator of a ship sees on his P.P.I. screen as he approaches the entrance of a narrow strait. The 15 sea-mile range scale is in use, which means that the full trace from the centre of the tube to the circumference indicates 15 sea-miles or 30,000 yards. As he is working with stabilised position the heading line indicates his course—340°—with reference to true north. The next set of drawings shows the navigation of the strait itself.

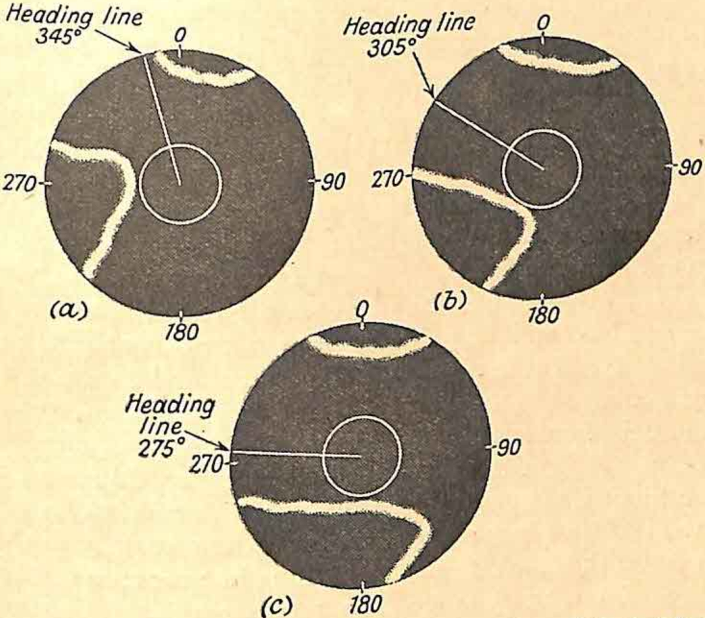

FIG. XVI. 9.—Showing how the range marker may be used in rounding a headland in thick weather. The $2\frac{1}{2}$-mile range-scale is now in use.

From the chart the navigating officer decides that in the prevailing weather conditions he should give the headland to the south of the mouth of the strait a berth of 1,500 yards. Presently he switches over to the $2\frac{1}{2}$ sea mile (5,000 yard) range, and adjusts the range marker ring to 1,500 yards. His object, as illustrated in Fig. XVI. 9 (*a*), (*b*) and (*c*), is now to make the range marker ring appear to roll round the headland like the rim of a wheel. So long as he makes the changes in course necessary to bring this about on the screen of the P.P.I. tube he is keeping his ship at a distance of 1,500 yards from the headland. In Fig. XVI. 9 (*a*) the course has been altered to 345°; as the "rolling round" proceeds it is altered to 305° (Fig. XVI. 9 (*b*), and finally to 275° (Fig. XVI. 9 (*c*)). Thus his radar set does more than give him a clear picture of a coastline; it enables him in any state of the weather to keep at just the required distance from any point of danger. Radar navigation makes not only for safe navigation, but also for the most economical navigation, since the ship using it can take the shortest possible course consistent with safety.

When a ship is in the open sea the relative position is generally used. The only targets then are other ships, and it is convenient to observe their positions and courses with reference to the navigator's own course. But when he is in the neighbourhood of land the navigator usually finds it simpler to switch to stabilised, or "north-upwards" position. Charts are always drawn with north at the top, and it is thus easy to compare the radar picture with that seen on the chart. From the heading line the true bearing needed for any change of course is readily obtainable. Another great advantage is that when the course is altered it is the heading line that changes its position on the screen, giving a faithful indication of what is being done.

Were relative position used in circumstances like those illustrated—Figs. XVI. 8 and 9, the heading line would remain fixed at "twelve o'clock" on the screen and the targets representing the coastlines would move with each change of course. You may care to amuse yourself by redrawing these figures to show what the navigator would see, were relative position in use.

We may be proud of the fact that British shipborne radar is a long way ahead of that of any other country. The chief reason for this is that our Ministry of Transport determined in 1946 to take a most important step. It decided that the lessons learnt from wartime experience had proved that radar using a wavelength of about three centimetres could give merchant ships all that they needed or were likely to need for many years to come. An assembly consisting of delegates from more than twenty nations with maritime interests was convened in London and the Ministry put before them its suggestions for a detailed performance specification for marine radar sets.

There was almost unanimous agreement on every point of the specification: it was felt that it would meet all the needs of navigators. But some countries did not want to commit themselves to three centimetres, whilst others were not ready to bind their manufacturers to so strict and exacting a specification.

The result was that, alone amongst all countries, Britain issued a single specification for shipborne radar. Some foreign countries are still dilly-dallying between ten-centimetre, three-centimetre and ?-centimetre wavelengths; some can't make up their minds about the degree of accuracy to be laid down; some continue to haver over the minimum range at which a radar set should be able to give clear information.

Meantime, our manufacturers were able to go right ahead, with a specification to work on which remains far stricter than that in force in any other country. No shipborne radar set can receive the Ministry's certificate unless it complies with every detail of this specification. With their task clearly defined, our manufacturers got down to the job and were soon producing this apparatus. So well do radar sets made according to this specification supply the needs of shipping that the Ministry has guaranteed that no change of importance shall be made for many years.

Let me give just one example of the outstanding achievements of British marine radar. When a ship is sailing in narrow waters in thick weather it is of the utmost importance to her navigator to be able to "see" targets such as quays, buoys or other ships at very short range. If, for example, a pair of channel-marking buoys are 150 yards apart, the navigator cannot see both, and therefore be sure that he is passing between them, unless his radar can make objects no more than 75 yards away visible in its screen. The British standard is 50 yards. Many British radar sets can work at a range of only 35 yards, and one of the most recent has reduced this to less than 20 yards. On the other hand, the U.S.A. three-centimetre specification accepts 100 yards as the minimum range and there are at the time of writing few American shipborne sets capable of working at less than 80 yards.

In shipborne equipment radar is making one of its most immediate and more widespread contributions to the welfare of mankind. Even small ships, such as tugs, drifters, trawlers and coasters can accommodate the light and compact equipments now available. A much more difficult problem is to supply aeroplanes with radar equipment which is not only small enough and light enough for them to carry, but also capable of supplying all their needs. The aeroplane, remember, must know its height above the ground, as well as ranges and bearings, if it is to be able to fly safely in all weather conditions in mountainous country. The radio and other electrical equipment of 'planes is already so heavy in proportion to the weight that they can carry economically, that the provision of radar gear giving all the information that they require and yet not overburdening them, is a very difficult business, particularly where the smaller aircraft are concerned. It is a problem that will undoubtedly be solved; the miniature valves and other components now available are, in fact, enabling rapid advances to be made. Aircraft radar is good already; there is no information needed by the navigator of a 'plane which some kind of radar cannot furnish. It cannot be long before the small, lightweight, general-purpose radar set, fulfilling all the needs of the smaller 'planes, becomes a reality.

Quite apart from marine or aircraft radar, or even from the radar which makes use of electro-magnetic waves, there is another possible development of the pulse and echo method of locating targets which may have a wide range of applications in the future. This is based on the use of ultrasonic sound waves. Ultrasonic waves travel through air, but are so short that they are beyond the limited range of our ears. Their speed is the same as that of ordinary sound waves, and they can therefore be used over only short distances. Investigations have shown beyond a doubt that bats began to navigate by means of the pulse and echo method millions of years before man thought of it.

No doubt you have had the experience of being in a room in summertime when a bat, attracted by the light, has come in by the open window. It flies at dizzy speed about the room, yet never hits anything. At one instant it is flashing at full speed towards a wall; when only inches away from it this creature executes a lightning turn, neatly avoids at the last instant the wire by which an electric light is suspended, and is always able to save itself in time from the crash with some obstacle which seems to be inevitable. Bats have poor eyesight, especially in bright light, such as that of a room. How do they manage to save themselves when flying all out by taking avoiding action in the nick of time?

All the time that it is on the wing a bat makes short, sharp squeaks—pulses of sound—of such short wavelength that they are inaudible (or ultrasonic) to all but very young ears. It is the echoes of these pulses coming back from walls, wires, pillars and so on that enables the bat to turn or swerve in time.

In recent years much research has been going on in the production of ultrasonic waves, and many valuable uses have been found for them. In particular, a promising system has been developed to enable firemen equipped with pulse-sending and echo-receiving gear to find their way through smoke-filled buildings, where the eye could see nothing whatever.

The future may see many other useful applications on radar lines of ultrasonic technique. What, for instance, would drivers of cars, buses and lorries not give for a simple device which would enable them in the densest fog to know always the direction and the distance of the kerb and of the vehicle in front?

Radar is a very wonderful development of modern science. Already, it has enabled us to do regularly things which would have been considered impossible not many years ago. It is one of the youngest departments of applied science, for the history of the successful use by man of electro-magnetic waves to locate targets with precision dates back only a few years. That great advances in radar will continue to be made no one can doubt; with every one of these it will become still more useful to man and still more wonderful.

CHAPTER XVII

The Wonderful Magnetron

WE have seen already that radar could not provide closely accurate measurements of bearings and angles of sight until a means was found of concentrating the output of the transmitter into a narrow beam. To do this, waves of very short length and enormous frequency must be used, for with these alone can the aerial system needed to produce a narrow "pencil" of radiation be of reasonably small size. Wireless waves of the order of 10 centimetres (roughly 4 inches), with a corresponding frequency of 3,000 million cycles, or 3,000 megacycles a second, can conveniently be concentrated into a beam by the use of curved metal reflectors, which act in exactly the same way as the reflector of a motor car headlamp. When the wavelength does not exceed 10 centimetres these reflectors, or paraboloids, as they are called, are not of unwieldy size. With wavelengths much longer than this they would be too large and heavy and would offer too much resistance to winds to be of practical use.

Another important point is that the shorter the wavelength, the more clearly and sharply is the target shown up on the radar screen. This is of special moment in P.P.I. tube images: in 10-centimetre H_2S a town is seen on the screen as a rather smudgy patch of light, just identifiable by comparing its shape with that shown on the map. Reduce the wavelength to 3 centimetres and the frequency reaches the almost unimaginable figure of 10,000,000,000 cycles—10,000 megacycles—a second. But the results are spectacular: the blurred image becomes far clearer; individual features of the town may be recognisable. Could we continue the process of wavelength reduction, or frequency increase, a good deal further (and this will undoubtedly be done one day), we should achieve what has been aptly termed "radar television." The screen would show almost as clear and as detailed a picture of the town as that seen in a photograph taken in broad daylight from an aeroplane. We have not arrived at that point yet, nor indeed at anything like it; but we have reached a stage of development which enables airborne radar equipments, such as the latest form of H_2S and the marine radar apparatus carried by hundreds of merchant ships to-day, to give navigators clear-cut and unmistakable pictures of what is below them, if the craft in their charge are airborne, or around them if these are seaborne.

To effect this, some means had to be found of transmitting high-power pulses on very short wavelengths. The radio valve is a very wonderful piece of apparatus. Without it neither broadcasting nor television would be possible; nor could you put through a telephone call to a distant place in this country, or to one at the other end of the world, with the certainty that in the ensuing conversation you would both hear and be heard so well that distance between you and your correspondent had, for all practical purposes, been reduced to a few feet rather than hundreds or, maybe, thousands of miles. But the valve has its limitations.

It operates, as we saw when discussing the cathode-ray tube, through the control by the grid of the density of a stream of electrons, travelling from cathode to anode. To be able to deal adequately with a particular frequency a valve must be able to produce an increase in the density corresponding to each positive half-cycle and a decrease corresponding to each negative half-cycle. Electrons require a certain amount of time to pass from cathode to anode and this transit time, as it is called, begins to introduce difficulties when the valve is called upon to deal with frequencies of hundreds of megacycles. As the frequency increases from hundreds to thousands of millions of cycles a second the efficiency of the valve falls off so rapidly that a point is reached at which it becomes of no use as a generator of the high power needed for long-range radar. The effect of the transit time at such enormous frequencies is that the valve simply cannot work fast enough to keep in step with them.

Transit time can be reduced by placing cathode, grid and anode closer together; but there are limits beyond which this reduction in the spacing cannot go. Nor is transit time the only factor which goes to make for a marked lowering of the efficiency of any valve of the familiar type when the frequency is raised beyond a certain point.

The radar pulse sent out by the transmitter must be a powerful one, if there is to be sufficient "illumination" of a distant target by invisible radio waves. You will recall that on reaching the target, radiation is scattered in all directions—except, of course, directly behind the target. The proportion of the energy in the pulse which returns as the echo received by the radar aerial is almost incredibly minute. Further, this energy falls away to an amazing degree as the range is increased: using the same transmitter, the echo pulse from a target 10 miles away on the surface of the sea has only $\frac{1}{256}$ of the energy of that from one of the same size at 5 miles.

The power-output of a radio or radar transmitter is always measured in watts or kilowatts. For some reason it has become conventional to express electrical power in these units and mechanical power in horse-power. This is rather a pity, for it fosters the idea that they are altogether different kinds of power. They are not; for in every case the power is a measure of the rate at which work is done: power of any kind can be expressed equally well in either watts or horse-power. One watt is one-thousandth of a kilowatt and we can conveniently take 750* watts, or $\frac{3}{4}$ kilowatt, as the equivalent of 1 horse-power. Thus a 12-h.p. motor car could equally well be described as one of 9 kilowatts, or a 1-kilowatt electric fire as a $1\frac{1}{3}$ h.p. device. You can obtain some idea of what the watt and the kilowatt represent from everyday electrical appliances. The pocket flashlamp is made to light up by the expenditure of about 1 watt of power; motor car headlamps consume, as a rule, 36 watts; if you have electric light in your home, you know the illumination provided by lamp bulbs rated at 10, 15, 25, 40, 60, 75 and 100 watts, or the heat given out by 1-kilowatt or 2-kilowatt electric fires.

Radar sets of most kinds require the power put into the transmitted pulse to be of the order of tens or even hundreds of kilowatts. At the very high frequencies of which we are now thinking, the ordinary valve cannot give anything like this performance, even if it will work at all. An entirely new kind of valve known as the "Klystron" was developed in the United States during the late 1930's. It operated at frequencies far beyond those at which the ordinary valve threw up the sponge; but its output was far too small to enable it to be used as the source of output power in a radar transmitter.

If precision radar was to be realised, a valve of a completely different sort must be developed. Invented and developed it was, through the genius of two British scientists—Boot and Randall. The device which they evolved early in 1940 is now often called simply the magnetron. That is rather unfortunate, for the simple magnetron had been known for many years before that date. What Boot and Randall did was to perfect an entirely new kind of magnetron, the cavity magnetron, which was without a doubt the greatest single wartime invention. To-day, it is the heart of nearly all of the many types of radar equipment which are doing so much to increase the safety of travel by sea and by air.

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* Actually 746.

Though it may be no bigger than two shoe-polish tins clapped together (and of much the same shape), the cavity magnetron can and does act as a generator of power measured in kilowatts on frequencies up to 10,000 megacycles and beyond. It has made it possible to produce long-range, high-precision radar sets of such small size and weight that they can be carried by little ships, such as colliers and trawlers, and by aircraft of most kinds.

Exactly how the cavity magnetron works is still a matter of debate amongst physicists and mathematicians. We can, though, form a good general idea of its principles without plunging into deep waters.

In Chapter III we saw that a piano string vibrates always at one particular frequency when struck by the hammer. In scientific parlance the string is excited by the impact of the hammer and vibrates at its natural frequency. Other things besides stretched strings have natural frequencies and may be excited in a variety of ways. Everyone in the days of his or her noisy youth has produced (Fig. XVII. 1) piercing notes by blowing into the hollow shaft of a key. The stream of air excites the walls of the tube, which vibrate at a natural frequency depending on their thickness and the size of the hollow that they enclose. The principle of all wind instruments, from the penny whistle to the oboe or the bombardon, is that the walls of a rigid tube vibrate, when excited, at a natural frequency depending on their thickness and the diameter and length of the tube. A musician cannot alter at will the thickness of the walls of his instrument, or its diameter; but he can and does alter its effective length by opening or closing holes in it and letting the compressed air within escape after a shorter or longer journey. The vibrations of string, tube, bell or drum set up air waves consisting of high-pressure crests and low-pressure troughs.

Electro-magnetic waves are set up in a similar way by excitation. We call their far more rapid vibrations "oscillations." The aerial of a broadcasting station is tuned—just as a piano string is tuned, though in a different way—to the particular natural frequency assigned to the station. The transmitter excites this aerial and causes it to oscillate, with the result that it sends out a train of electro-magnetic waves at its natural frequency. To tune in the station you adjust your receiving set until it has the same natural frequency: it then responds to the transmission that you want to receive and to no other. You have, possibly, not realised that you do anything so complicated or so clever when you tune in a broadcasting station; but you do, for all that!

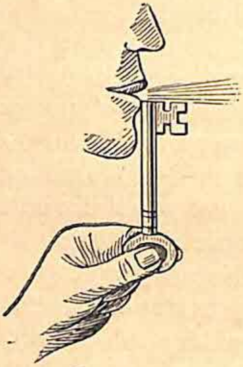

FIG. XVII. 1.

The cavity magnetron produces oscillations in very much the same way as the excited key of Fig. XVII. 1 produces sound waves. There is a similar blast against the walls of a cavity and a similar fixing of the natural frequency by the size of the cavity. The great difference is that the exciting force is not a stream of air, but a stream of electrons. Fig. XVII. 2 illustrates the body of the magnetron. The anode consists of a thick disc of solid metal in which a number (usually eight) of equally spaced cavities are drilled. Each cavity has a slot connecting it with the large circular hollow in the middle.

At the centre of this hollow is the tubular cathode, or source of electrons. As in the valve and the cathode-ray tube, the anode is strongly positive to the cathode, so that electrons flung out by the cathode are drawn at high speeds towards the anode owing to the electric field between the two.

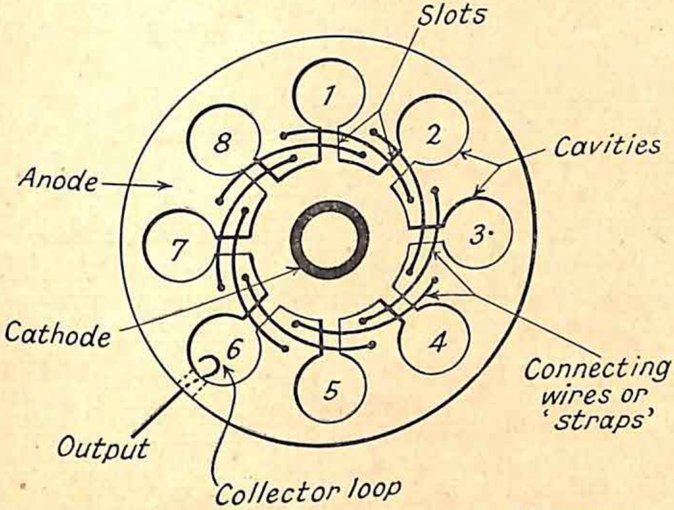

FIG. XVII. 2.—The body of the Strapped Cavity Magnetron.

If there were nothing else to influence their movements, there would be just a cloud of fast-travelling electrons passing from the outer surface of the cathode to the inner surface of the anode.

But there is something else; and a very important something it is. The body of the magnetron is sealed between two "lids" which are not shown in the drawing. Within the body there is a high vacuum. The body is mounted between the poles of a powerful magnet (hence the name "magnetron"), so placed that the magnetic field exerts a pull on the electrons at right angles to the pull of the inside electric field. When looking at Fig. XVII. 2, you must imagine this field as extending from your eye straight through the page.

If there were only an electric field, the electrons would, as we have seen, travel from cathode to anode. Were there nothing but a magnetic field acting on a cloud of electrons, these would move in circular paths round the centre instead of travelling straight outwards. The combination of electric and magnetic fields causes individual electrons to make all kinds of queer journeys inside the magnetron. But the result on the whole cloud of electrons is that they group themselves into a formation rather like four spokes of a rimless wheel. The wheel is not stationary: it rotates millions of times every second. The tips of the "spokes" brush against the walls of the slots and excite the cavities into oscillation at their natural frequency. It is the small boy and the key all over again; but this time the exciting agent is a whirlwind of electrons.

The magnetron works most efficiently when the currents due to the oscillations are in the same direction in alternate cavities and in the opposite direction in the intervening cavities. If currents are clockwise in Nos. 1, 3, 5 and 7, they must be anti-clockwise in Nos. 2, 4, 6 and 8. In early models it was found difficult to maintain this state of affairs. The cavities were liable to slip, so to speak, out of step with one another, and when this took place there was a big falling off in the output. By a stroke of genius a

Birmingham physicist, J. Sayers, introduced the "strapped" magnetron, in which (as shown in Fig. XVII. 2) the odd-numbered cavities are all connected to each other by wires, the even-numbered cavities being similarly strapped together. This maintains the alternate clockwise and anti-clockwise currents, and the strapped cavity magnetron can be relied upon to work always at full efficiency.

The power generated in the magnetron is tapped off by a wire loop, which looks rather like a buttonhook, placed in one of the cavities. And the magnetron is a generator of high power even on wavelengths of 1 centimetre or below, which correspond to frequencies of 30,000,000,000 cycles—30,000 megacycles—a second or more. Modern magnetrons enable "microwave" radar pulses to be sent out with a peak power of 25 to 50 kilowatts.

The magnetron is doing marvellous work to-day on the airways and in the airports, on the sea lanes and in the harbours of the world. This work is growing rapidly in scope and in importance as radar becomes more and more widely recognised as the most wonderful of the aids to navigation that man possesses.

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